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Major- and Trace- Element Geochemistry of Kimberlitic Rocks in Northern Alberta

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Abstract

During the 1990s, kimberlitic rocks were discovered in three separate areas of northern Alberta. These pipes comprise mainly lapilli-bearing olivine crystal tuff and volcaniclastic rocks that are interpreted to be pyroclastic crater facies. Eighty-three bulk rock samples were collected from the Mountain Lake cluster, and Buffalo Head Hills and Birch Mountains fields for analysis of major and trace elements. To place these data in context, the compositions are compared to kimberlite and ultramafic occurrences worldwide.

This report provides data that allow for geochemical distinction between kimberlitic fields in northern Alberta. Samples from the Mountain Lake pipes and the Buffalo Head Hills and Birch Mountains fields contain low SiO_2 and Na_2O/K_2O, with Cr, Ni, MgO, rare-earth elements (REE), Zr and Nb concentrations elevated relative to their abundance in common crustal rocks.

Samples from the Buffalo Head Hills and Birch Mountains have close geochemical affinities with Group I South African kimberlites. Of the two areas, the Buffalo Head Hills kimberlites contain the highest MgO, Cr and Ni, the lowest Al_2O_3, SiO_2, V, Y, Pb, Sr and Ga values, and have chemistry similar to that of primitive kimberlite in the Northwest Territories. In addition, a high proportion of the Buffalo Head Hills kimberlites are diamondiferous. The Buffalo Head Hills field may therefore be classified as the more primitive kimberlite magma in this dataset. In contrast, the Birch Mountains kimberlites are more evolved, with lower SiO_2, Ni and Mg#, and higher Fe_2O_3, TiO_2, Nb, V, Sc, Zr, Hf, Y, Ba, Rb, light rare-earth elements (LREE), Ga and Pb.

A linear trend is found for northern Alberta kimberlite, which reflects compositional evolution from primitive to evolved kimberlite magmas. Northern Alberta pipes with elevated contents of diamonds generally have similar chemistry and reside on the primitive end of this trend line. This study will therefore enable exploration companies to compare future discoveries of kimberlite with these results for a quick and economical evaluation of a prospective target.

The Mountain Lake pipes are not kimberlite, but rather a hybrid rock with geochemical affinities to basanite (olivine potassic basalt), the Sweet Grass olivine minette and Montana alnöite. Compared to northern Alberta kimberlite (Buffalo Head Hills and Birch Mountains), the Mountain Lake pipes contains higher SiO_2, Al_2O_3, Na_2O, K_2O, Na_2O/K_2O, Ga, Rb and peralkalinity index, and lower MgO, Nb, LREE and Sr.

1. Introduction

Kimberlitic pipes have been discovered in three separate areas of northern Alberta (Figure 1). In 1990, Monopros Limited discovered the Mountain Lake North and South pipes, located northeast of Grande Prairie, by sampling of diamond-indicator minerals. In 1997, Ashton Mining of Canada Inc., in a joint venture with Alberta Energy Company and Pure Gold Resources Ltd., discovered kimberlites on the southeast flank of the Buffalo Head Hills. By April 2001, Ashton has discovered 36 pipes. Ashton reported that kimberlite K252 contained 66.2 carats per hundred tonnes (cpht) from a 1.28 tonne sample and plans to bulk sample the kimberlite in 2001 (Ashton Mining of Canada Inc., 2000a). In addition, Ashton confirmed the presence of large stones (e.g., K252 contained 0.85 carats of stones greater than 0.8 mm in size). In 1998, Kennecott Canada Exploration Inc., in conjunction with Montello Resources Ltd., and Redwood Resources Ltd. discovered seven kimberlites in the Birch Mountains area. Active exploration continues in all three areas, as well as other parts of Alberta. For example, in December 2000, New Blue Ribbon Resources Ltd. reported a new kimberlite discovery in the Birch Mountains, which brings to eight the number of pipes found in the Birch Mountains area.

This report is the first in a series of studies on the petrogenesis of Alberta kimberlitic rocks. Ultimately, we will document the physical (e.g., texture, classification), and geochemical (e.g., major and trace element, isotopic) characteristics of the pipes. The results will be released in logical 'groupings' to facilitate rapid dissemination of information and interpretations.

In this report, we present whole-rock major- and trace-element data for samples from the Mountain Lake, Buffalo Head Hills and the Birch Mountains areas. To place these data in context, we compare the compositions of the Alberta samples to each other, and to kimberlite and other alkali rock types worldwide.

Major- and trace-element geochemical studies of kimberlites are hindered by the ubiquitous presence of crustal, xenolithic and xenocrystic material. Because pipes in northern Alberta are dominated by pyroclastic and resedimented volcaniclastic rocks (e.g., Leckie et al., 1997; Carlson et al., 1998; Wood et al., 1998), one might expect that bulk geochemistry is of limited potential for the purpose of rock classification. As noted by Mitchell (1986) and Mitchell and Bergman (1991), however, ultramafic alkaline rocks such as kimberlites are characterized by elevated contents of first- and second-period transition elements, alkali and alkaline earth elements, and lanthanides relative to common igneous and sedimentary rocks. Many of these elements are relatively immobile during weathering and deuteric alteration processes, because they are hosted in insoluble relict primary and secondary phases, or insoluble in low-temperature fluids. The absolute abundance of many of these elements may therefore change slightly, but the ratios of these elements should remain unchanged. Therefore, these authors argue that bulk-rock geochemistry may be particularly useful in assessing the character of volcaniclastic and epiclastic sedimentary rocks in crater facies, where highly altered rocks may be difficult to identify by optical or electron beam methods. Given that the Alberta pipes appear to be highly altered, we decided to see if whole-rock geochemistry could provide useful information on these samples.

2. General Geology, Sampling and Analytical Methods

Brief descriptions of the ultramafic pipes discovered in the Mountain Lake, Buffalo Head Hills and Birch Mountains areas are provided below. In addition, section 2.4 describes some of the rock types used for geochemical comparisons with the Alberta samples.

Figure 1. Generalized geology of Alberta (from Hamilton et al., 1997), showing reported occurrences of alluvial diamonds and kimberlitic rocks in Alberta and southeastern British Columbia.

2.1 Mountain Lake

Seventeen samples of core were collected from two drillholes completed during a 1995 drill program conducted jointly by the Alberta Geological Survey (AGS) and Geological Survey of Canada. The core was used to describe the petrology, indicator minerals, aeromagnetic signature, age, stratigraphic position and setting of the Mountain Lake pipes by Leckie et al. (1997). Leckie et al. (1997) classified the Mountain Lake body as an alkaline ultrabasic volcanic rock. In thin section, the drillcore consists of pyroclastic material, mainly olivine-rich juvenile lapilli tuff with euhedral to anhedral olivine that has been completely altered to clay minerals and serpentine. Other coarse constituents include rare ultramafic and basement xenoliths. The lapilli consist of devitrified vesicular glass (serpentine) and microcrystalline phlogopite-biotite mica, clinopyroxene, spinel, rutile, perovskite and apatite. Whole-rock geochemistry was not done for the Leckie et al. (1997) study. Eight samples, including two duplicates, were taken from core from drillhole ML95-1 and nine samples, including two duplicates, were taken from core from drillhole ML95-3.

The volcanic rocks have been found in outcrop at two separate near-surface exposures, Mountain Lake South (hole ML95-3) and North (hole ML95-1). Mountain Lake South forms a pronounced topographic high and measures 400 by 650 m (29 ha), whereas Mountain Lake North has no topographic expression and measures about 250 by 350 m (8.75 ha), as defined by the boundary of a weakly positive groundmagnetic signature. Based on drillcore samples, the Mountain Lake South body is composed mainly of juvenile-rich volcaniclastic rocks. Palynology results were used by Wood et al. (1998) to infer an emplacement age of mid-Maastrichtian, probably 68 Ma.

The magmatic material is variably contaminated by clasts of sandstone (possibly Wapiti Formation) and shale (possibly Kaskapau Formation). In addition, there is contamination of the groundmass of these samples by quartz and feldspar xenocrysts, presumably from the Wapiti Formation. The contamination varies from moderate to high in ML95-1 and is minimal in ML95-3.

Mineral separates of bulk rock samples were processed to obtain kimberlite indicator minerals. Chrome pyrope garnets, chrome diopside, orthopyroxene, chromite, picroilmenite and hydrogrossular garnet were found. The heavy-mineral concentrates from pyroclastic units within the pipes include Ti-rich, Cr-poor Group 9, Group 11 and Group 12 pyrope garnets (G9, G11 and G12; Dawson and Stephens, 1975), and Mg-rich picroilmenites (Eccles et al., 1997).

2.2 Buffalo Head Hills

Thirty samples, including two duplicates, were collected from hand-sized core samples provided by Ashton Mining of Canada Inc. The sample set includes rock material from sixteen individual pipes, although some pipes may be part of a single, larger complex (e.g., kimberlite complex K14 includes samples from targets K14, K14B and K14C). The low number of duplicate samples is due to an effort to preserve sample material for AGS display purposes. The geological information in this section is summarized from Carlson et al. (1998, 1999).

Inferred sizes of the pipes, based on aeromagnetic signatures and drilling, range from less than 1 ha to approximately 45 ha. Radiometric U-Pb dates of 86 ± 3 Ma and 88 ± 5 Ma on perovskite from the kimberlites (Carlson et al., 1998) are consistent with emplacement into sedimentary rocks of the Middle to Late Cretaceous (Cenomanian to Campanian) Smoky Group, the Dunvegan Formation and possibly the Shaftesbury Formation of the Western Canada Sedimentary Basin.

Preliminary petrographic examination of the kimberlites indicates that they consist mainly of lapilli-

bearing olivine crystal tuff, stratigraphically dominated by normally graded beds of coarse ash to coarse crystal tuff. Juvenile lapilli-rich beds have also been observed. Spherical or amoeboid lapilli, ovoid olivine macrocrysts up to 1 cm in length, and occasional mica laths up to 5 mm in length occur in a groundmass that typically consists of a fine-grained, sometimes segregational assemblage of serpentine, dolomite, calcite and chlorite. Mica microphenocrysts show core-to-rim evolution from phlogopite toward aluminous phlogopite (Carlson et al., 1998), and plot along Mitchell's (1995) kimberlite trend in Al_2O_3-TiO_2 composition space. Carlson et al. (1998) also reported that spinel microphenocrysts exhibit compositional magmatic trend 1, which Mitchell (1995) associated with Group I kimberlites.

Crustal xenoliths consist of shale, predominately of the Shaftesbury Formation. Mantle-derived xenoliths include peridotitic (lherzolite, wehrlite and harzburgite), pyroxenitic, eclogitic, and corundum- and spinel-bearing rock types. Textures of the mantle xenoliths vary from coarse granular to coarse tabular and porphyroclastic sheared styles.

Xenocrysts, presumably derived from mantle peridotite and pyroxenite, include olivine, chrome pyrope and calcic knorringitic garnet, chrome diopside and augite, enstatite, and aluminous magnesium chromite. Kimberlites in the northern part of the Buffalo Head Hills field contain subcalcic (G10) garnets with chromium contents of up to 17.8 wt. % Cr_2O_3, whereas the southern pipes contain only rare G10 garnets. Aluminous magnesium chromites generally contain between 30 and 62 wt. % Cr_2O_3, and the number of chromite grains with diamond-inclusion chemistry (>60 wt. % Cr_2O_3 and 12–17 wt. % MgO) is highly variable from one pipe to the next.

2.3 Birch Mountains

Thirty-six samples, including four duplicates, were collected from split drillcore and one surface sample (ultramafic rock clast discovered in glacial sediment directly over the Legend pipe). The samples are from seven separate pipes. The general geology presented here was compiled from Montello Resources Ltd. and New Blue Ribbon Resources Ltd. news releases, and from Aravanis (1999).

The approximate sizes of the pipes, which are inferred from magnetic anomalies (Montello Resources Ltd., 1998), are between 200 by 200 m (1 ha) and 1400 by 150 m (21 ha). The Phoenix kimberlite was dated at ca.71 Ma, using U-Pb from perovskite and K-Ar from phlogopite (Montello Resources Ltd., 1999). Palynologogical analysis on shale clasts extracted from the Phoenix pipe yielded Upper Cretaceous ages ranging from Campanian to Maastrichtian, consistent with an emplacement age for the kimberlite of 82 Ma (Montello Resources Ltd., 1998).

In thin section, the kimberlite consists of a fine-grained serpentine-smectite-carbonate matrix that contains olivine microcrysts and macrocrysts (Aravanis, 1999). The olivine is usually fresh, partially serpentinized or totally replaced by dolomite and magnesite. The rock also contains rare macrocrystalline phlogopite and disseminated macrocrystalline and microcrystalline ilmenite. Some samples contain several generations of juvenile lapilli, possibly indicating that some of the pipes consist of resedimented pyroclastic material.

The country rock fragments are typically black angular clasts of shale and green, subangular to rounded clasts of argillite and rare carbonate. Macroscopic examination of the drillcore from the seven kimberlites discovered in 1998 and 1999 revealed few to no mantle xenoliths or xenocrysts in these samples. However, the Kendu kimberlite (discovered in December 2000) is characterized by an abundance of mantle xenocrysts in conjunction with a large percentage of lherzolite and eclogite xenoliths (New Blue Ribbon Resources Ltd., 2001).

Reported heavy-mineral chemistry of the Birch Mountains kimberlites indicates that they contain abun-

dant olivine and ilmenite, and rare chromite. The compositions of the olivine grains (Fo_{88-92}) are typical of mantle peridotite and kimberlite. The ilmenite grains are Mg-rich, which Montello Resources Ltd. (1998) reported as favourable for the preservation of diamonds. According to New Blue Ribbon Resources Ltd. (2001), the Kendu kimberlite contains high-chrome pyrope, lherzolitic garnet, eclogitic garnet, high-Mg picroilmenite, chrome-rich clinopyroxene and spinel.

2.4 Comparative Rock Descriptions

Despite quite variable characteristics (e.g., mineralogy and whole-rock chemistry), a wide spectrum of magmas ranging from alkali basalt to kimberlite has been considered by Green (1971), Frey et al. (1978), Alibert et al. (1983), and Rogers et al. (1992) as being generated by a small degree of partial melting in the lithospheric to sublithospheric mantle. These magmas are considered to have developed at different source depths, under different physical conditions, and potentially from different rock types. This variability corresponds to a variety of magma types within or near kimberlite clusters. For example, kimberlite and melilitite coexist at Namaqualand, South Africa (Rogers et al., 1992) and in the Bargydamalakh pipe, Anabar region, USSR (Ukhanov, 1963). In the Sarfartoq region of western Greenland, a continuum of rock composition ranges from kimberlite through ultramafic lamprophyre to dolomitic carbonatite (Larsen and Rex, 1992; Dalton and Presnall, 1998).

In addition to variability resulting from the melting process, the chemistry of kimberlites can be altered by contamination (variable amounts and types of crustal fragments from the country rock into which they intrude) and alteration (associated with late-stage degassing and/or groundwater circulation) processes that have been thoroughly documented (e.g., Ilupin and Lutz, 1971; Clement, 1982; Mitchell, 1986). Past studies (e.g., Ilupin and Lutz, 1971) experimented with separating and analyzing the groundmass of kimberlite with relative success. Fesq et al. (1975) noted that the 'groundmass approach' does not overcome the effects of the presence of finely comminuted particles in the groundmass of kimberlites or the possibility of contamination by assimilation, where the assimilating material is incorporated by partial fusion.

To attempt a classification of the kimberlitic rocks from Alberta, and to place these samples in a global context, the major-element geochemical data from Alberta samples are compared to compositions of kimberlites and alkaline rocks worldwide. We include selected geochemical data for kimberlite, alkali basalt (basanite), minette, alnöite and melilitite. A brief description for each of these rock types follows.

Kimberlite shows a wide range in composition, but a number of general statements can be made regarding its chemistry. It is low in SiO_2 (25–30 wt. %), low in Al_2O_3 (usually <5 wt. %) and very low in Na_2O (usually < 1 wt. %). On the basis of mineralogy, chemistry, age, and isotopes, kimberlite has been divided into Group I and Group II types (e.g., Smith et al., 1985). Group I kimberlite is generally non-micaceous, Cretaceous (90–114 Ma) in age and has a radiogenic isotopic signature similar to many ocean island basalts (OIB). In contrast, micaceous Group II kimberlite is derived from ancient (>1 Ga), trace-element–enriched sources situated within the subcontinental lithosphere. Geochemical averages for Group I and Group II global kimberlite and average kimberlite in this report are taken from Dawson (1967), Ilupin and Lutz (1971), Gurney and Ebrahim (1973), Ilupin et al. (1974), Scott (1979), Muramatsu (1983), Zhang and Liu (1983), Smith et al. (1985), Mitchell (1986), Taylor et al. (1994), Mitchell (1995), Berg and Carlson (1998), and Price et al. (2000).

Basanite (alkali olivine basalt) comprises abundant olivine (including in the groundmass), labradorite-andesine and modal nepheline (or analcime and leucite). In general, basanitic rocks contain low SiO_2 (43.01–45.54 wt. %), high MgO (7.57–10.74 wt. %), high Al_2O_3 (11.94–14.70 wt. %) and Na_2O (3.26–4.06 wt. %). Le Bas (1989) suggested that the distinction between basanitic and nephelinitic rocks

be based on the presence of plagioclase in basanite. This report uses the geochemical averages for worldwide basanitic rocks (Le Maitre, 1976) and basanite data compiled by Le Bas (1989) that includes examples from the USSR (Andreeva et al., 1983), Anjouan, Comores Island (Flower, 1973) and central Spain (Ancochea and Ibarrola, 1982).

The Sweet Grass Intrusives, located in the Milk River area of southern Alberta, comprise 48 Ma (K-Ar biotite; Currie, 1976) and 49 to 52 Ma (K-Ar; Hearn et al., 1978) potassic igneous rocks. On the basis of bulk-rock major- and trace-element geochemical parameters, as well as zoning trends in mica phenocrysts, the rocks have been classified mainly as minette (Kjarsgaard, 1994; Buhlmann et al., 2000). Sweet Grass olivine minette geochemical data used in this study are from Kjarsgaard (1994) and Buhlmann et al. (2000). Mitchell and Bergman (1991) demonstrated that most minettes plot in the field for Roman Province type (RPT) lavas on the plot of SiO_2 versus molar $([K_2O+Na_2O]/Al_2O_3)$. These metaluminous potassic lavas are relatively rich in SiO_2 (>42 wt.%) and typically contain Al-rich pyroxenes, Fe-poor leucite and sanidine, and plagioclase (Barton, 1979). Where applicable, RPT geochemical data described by Mitchell and Bergman (1991) and Mitchell (1995) are included in this study.

The 41 to 51 Ma alkalic ultramafic magmas in north-central Montana consist of a variety of rocks, including alnöite, monticellite peridotite, carbonate-rich mica peridotite, and kimberlite (Hearn, 1986). The rock types show a continuum of major- and trace-element compositions, and have overlapping ranges of MgO content (10–25, 19–30, 24–31 and 23–32 wt. %, respectively). Thus, the geochemical data from the Haystack Butte and Winnett Sill were selected and used in this study as representative alnöite (melilite-bearing, 10–25 wt. % MgO) from the Montana ultramafic complex (Hearn, 1986).

Melilitite has been described as the most mafic member of the alkali basalt series (Le Bas, 1989; Rock, 1991; Wilson et al., 1995). It has high Mg and contains ultramafic inclusions of high-pressure origin, and is therefore a likely candidate for a primary magma composition (Brey, 1978). Le Bas (1989) classified olivine melilitite as having low SiO_2 (<40 wt. %) and Al_2O_3 (<11 wt. %), high MgO (>14 wt. %) and TiO_2 (>22 wt. %), and relatively low alkali contents (Na_2O/K_2O ratio of 1.65–1.86). Melilitite is extremely enriched in incompatible elements, especially Nb and light rare-earth elements (LREE). Melilitite geochemical data from Rogers et al. (1992) and Wilson et al. (1995) are used for geochemical comparisons in this report.

2.5 Analytical Methods

The eighty-three samples, including ten randomly picked duplicates, were sent to ACME Analytical Laboratories Ltd., Vancouver, British Columbia. Preliminary macroscopic sample descriptions are presented in Appendix 1. The samples were crushed to less than 2 cm at the AGS and large, visible, country-rock xenoliths (shale and carbonate) were removed. The samples were dried at 60°C, pulverized to -150 mesh using a chrome-steel ring-and-puck pulverizer at ACME and analyzed by ACME using the following protocols:

- Group 4A total decomposition using $LiBO_2$ fusion followed by HNO_3 acid dissolution and analysis by inductively coupled plasma optical emission spectroscopy (ICP-OES)
- Carbon and sulphur by Leco carbon analyzer
- Group 4B total decomposition and analysis (same as above) for minor and trace elements, including rare-earth elements
- Base metals by aqua-regia digestion followed by inductively coupled plasma mass spectroscopy (ICP-MS)

The analytical precision quoted by ACME is 5% and 10% for Groups 4A and 4B, respectively. Nickel was analyzed by $LiBO_2$ in Group 4A and by aqua-regia digestion in Group 4B.

The major- and trace-element analytical data are presented in Appendices 2 and 3, respectively. Scatter-plot matrices of selected major and trace elements for the Mountain Lake, Buffalo Head Hills and Birch Mountains areas are presented in Appendices 4A, 4B, and 4C, respectively.

3. Major-Element Geochemistry

3.1 Contamination and Alteration

The duplicate analysis of ten randomly selected sample separates from drillcore yielded a relative error for the major elements of <6.5% (Table 1), as defined by the standard deviation divided by the mean (Le Maitre, 1982). With the exception of Na_2O and K_2O, which have relative errors of 5.6% and 6.5%, the analytical reproducibility of the duplicate samples is less than 3.7% for the major-element oxides SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, TiO_2, P_2O_5, MnO and Cr_2O_3. The high relative errors for oxides such as Na_2O are reflected by the wide range of Na_2O content. Samples with low Na_2O content, such as ABK59 (0.04%) and its duplicate sample ABK60 (0.4%), have a high relative error of 20%. Samples with high Na_2O content, such as ABK32 (2.31%) and its duplicate sample ABK33 (2.29%), have a much lower relative error (1%). These differences may reflect the precision of the analytical technique.

Tests proposed by Clement (1982), Mitchell (1986), Taylor et al. (1994) and Berg (1998) are used below to determine the type and extent of contamination. Clement (1982) used the contamination index (C.I.) to measure the proportion of clay minerals and tectosilicates relative to olivine and phlogopite:

$$\text{C.I.} = \frac{SiO_2 + Al_2O_3 + Na_2O}{MgO + K_2O}$$

Clement (1982) found that uncontaminated Group I kimberlite has a C.I. near 1.0, but that some apparently fresh and contamination-free micaceous Group II kimberlite has a C.I. up to 1.5. Of the samples analyzed during this study, all of the Mountain Lake, 33% of the Birch Mountain, and 7.5% of the Buffalo Head Hills samples have a C.I. of greater than 1.5 (Figure 2; Appendix 2).

Taylor et al. (1994) used the ilmenite index (Ilm.I.) to identify kimberlite that potentially contains accumulated xenocrystalline or megacrystalline ilmenite:

$$\text{Ilm.I.} = \frac{(FeO_t + TiO_2)}{(2K_2O + MgO)}$$

Taylor et al. (1994) suggested that the Ilm.I. of type A nonmicaceous kimberlite (South African Group IA) and micaceous kimberlite (South African Group II) should not exceed 0.52 and 0.47, respectively. They further suggested that the limit for nonmicaceous type B kimberlite (South African Group IB) is difficult to judge due to its relatively high bulk-rock TiO_2 content. Of the samples analyzed during this study, 3% of the Mountain Lake, 6.7% of the Buffalo Head Hills, and 36% of the Birch Mountains samples have an Ilm.I. of greater than 0.52 (Figure 2; Appendix 2).

The plot of C.I. versus of Ilm.I. in Figure 2 indicates that the compositions of Alberta kimberlitic rocks differ depending on their location:

Table 1. Duplicate samples from Alberta kimberlitic rocks with geochemical data and relative error.

Duplicate Pairs: Major Elements

Sample No.		SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MgO %	CaO %	Na_2O %	K_2O %	TiO_2 %	P_2O_5 %	MnO %	Cr_2O_3 %	Ba ppm	Ni ppm	Sc ppm	LOI %	C_{tot} %	S_{tot} %	SUM %
ABK12		28.89	1.63	7.66	29.11	11.78	0.09	0.15	0.80	0.47	0.11	0.14	535.00	1524.00	10.00	18.60	2.69	0.17	99.67
ABK13		28.92	1.62	7.77	29.34	11.48	0.09	0.14	0.84	0.51	0.10	0.15	559.00	1582.00	10.00	18.70	2.62	0.14	99.93
	Relative error	0.00	0.00	0.01	0.01	0.02	0.00	0.05	0.03	0.06	0.07	0.05	0.03	0.02	0.00	0.00	0.02	0.14	0.00
ABK17		29.47	2.54	8.62	35.41	6.02	0.09	0.22	0.48	0.41	0.14	0.15	959.00	1298.00	10.00	15.90	5.89	0.32	99.72
ABK18		30.49	1.95	8.55	38.06	5.41	0.07	0.15	0.45	0.38	0.14	0.15	909.00	1429.00	10.00	13.60	5.58	0.31	99.69
	Relative error	0.02	0.19	0.01	0.05	0.08	0.18	0.27	0.05	0.05	0.00	0.02	0.04	0.07	0.00	0.11	0.04	0.02	0.00
ABK32		59.21	11.15	5.92	7.42	2.68	2.31	2.93	0.76	0.23	0.09	0.06	992.00	204.00	12.00	6.90	0.87	0.37	99.80
ABK33		59.99	11.49	5.44	6.97	2.67	2.29	3.10	0.79	0.22	0.08	0.06	1044.00	271.00	13.00	6.70	9.01	2.91	99.95
	Relative error	0.01	0.02	0.06	0.04	0.00	0.01	0.04	0.03	0.03	0.08	0.06	0.04	0.20	0.06	0.02	1.17	1.10	0.00
ABK36		61.24	11.23	5.26	6.46	2.96	2.66	2.16	0.75	0.22	0.09	0.06	911.00	204.00	13.00	6.20	0.82	0.12	99.42
ABK37		61.61	11.35	5.38	6.48	2.71	2.55	2.15	0.73	0.20	0.09	0.06	945.00	197.00	13.00	6.10	0.72	0.14	99.54
	Relative error	0.00	0.01	0.02	0.00	0.06	0.03	0.00	0.02	0.07	0.00	0.02	0.03	0.02	0.00	0.01	0.09	0.11	0.00
ABK41		46.20	7.58	7.78	16.39	4.40	1.35	1.71	0.79	0.29	0.11	0.14	837.00	712.00	12.00	12.60	0.68	0.21	99.52
ABK42		47.14	7.89	7.18	15.75	4.72	1.39	2.16	0.85	0.31	0.11	0.14	915.00	721.00	13.00	11.90	0.68	0.24	99.73
	Relative error	0.01	0.03	0.06	0.03	0.05	0.02	0.16	0.05	0.05	0.00	0.01	0.06	0.01	0.06	0.04	0.00	0.09	0.00
ABK46		51.37	9.29	6.43	13.71	3.24	1.92	2.44	0.89	0.30	0.10	0.12	959.00	507.00	14.00	9.60	0.60	0.22	99.58
ABK47		51.51	9.42	6.39	13.43	3.21	1.83	2.58	0.89	0.28	0.10	0.12	990.00	487.00	14.00	9.60	0.64	0.24	99.53
	Relative error	0.00	0.01	0.00	0.01	0.01	0.03	0.04	0.00	0.05	0.00	0.02	0.02	0.03	0.00	0.00	0.05	0.05	0.00
ABK49		48.52	9.34	7.11	13.53	3.86	1.73	2.56	1.41	0.44	0.07	0.08	1344.00	355.00	14.00	11.00	1.48	0.48	99.84
ABK50		49.10	9.38	7.00	13.23	3.49	1.81	2.26	1.39	0.45	0.07	0.08	1114.00	337.00	14.00	11.40	1.42	0.50	99.82
	Relative error	0.01	0.00	0.01	0.02	0.07	0.03	0.09	0.01	0.02	0.00	0.01	0.13	0.04	0.00	0.03	0.03	0.03	0.00
ABK53		31.87	3.50	9.79	23.41	8.88	0.19	0.61	2.08	0.43	0.17	0.20	611.00	834.00	16.00	18.70	2.69	0.18	99.98
ABK54		32.33	3.46	9.63	23.37	8.71	0.18	0.56	2.11	0.43	0.17	0.21	709.00	859.00	16.00	18.30	2.52	0.25	99.65
	Relative error	0.01	0.01	0.01	0.00	0.01	0.04	0.06	0.01	0.00	0.00	0.05	0.10	0.02	0.00	0.02	0.05	0.23	0.00
ABK59		27.50	2.74	10.15	28.06	8.36	0.04	0.53	3.54	0.55	0.18	0.15	780.00	726.00	18.00	17.80	2.85	0.28	99.78
ABK60		27.42	2.74	10.25	28.04	8.54	0.03	0.58	3.53	0.54	0.19	0.15	789.00	712.00	18.00	17.60	2.91	0.30	99.78
	Relative error	0.00	0.00	0.01	0.00	0.02	0.20	0.06	0.00	0.01	0.04	0.01	0.01	0.01	0.00	0.01	0.01	0.05	0.00
ABK69		13.07	2.62	7.83	19.14	16.02	0.18	0.19	3.15	0.46	0.19	0.13	532.00	551.00	15.00	36.40	10.38	1.05	99.51
ABK70		12.76	2.65	7.46	19.15	16.15	0.19	0.20	3.10	0.41	0.19	0.13	552.00	547.00	15.00	37.00	10.57	0.78	99.52
	Relative error	0.02	0.01	0.03	0.00	0.01	0.04	0.04	0.01	0.08	0.00	0.00	0.03	0.01	0.00	0.01	0.01	0.21	0.00
Avg. relative error (%)		**0.92**	**2.78**	**2.17**	**1.64**	**3.18**	**5.78**	**8.12**	**2.12**	**4.16**	**1.89**	**2.57**	**4.90**	**4.25**	**1.13**	**2.47**	**14.62**	**20.36**	**0.08**

Duplicate Pairs: Trace Elements (INNA)

Sample No.		Co ppm	Cs ppm	Ga ppm	Hf ppm	Nb ppm	Rb ppm	Sn ppm	Sr ppm	Ta ppm	Th ppm	Tl ppm	U ppm	V ppm	W ppm	Zr ppm	Y ppm	La ppm	Ce ppm	Pr ppm	Nd ppm
ABK12		87.30	0.30	2.60	4.10	158.30	6.60	1.00	737.30	11.30	20.50	< .1	4.70	51.00	< 1	162.20	10.40	163.70	312.50	30.96	105.80
ABK13		91.40	0.30	2.10	4.50	172.50	6.10	2.00	773.70	12.50	22.90	0.30	4.80	53.00	< 1	175.00	11.10	176.40	341.80	33.69	112.60
	Relative error	0.03	0.00	0.15	0.07	0.06	0.06	0.47	0.03	0.07	0.06	BLLD*	0.02	0.03	BLLD	0.05	0.05	0.05	0.06	0.06	0.04
ABK17		87.20	0.50	3.90	2.00	121.20	10.00	1.00	691.20	8.20	22.40	< .1	3.00	75.00	< 1	87.50	6.90	128.20	229.60	20.11	58.00
ABK18		101.70	0.20	3.80	1.80	120.20	5.20	1.00	646.80	8.50	22.30	< .1	3.00	69.00	< 1	78.50	6.40	107.90	190.30	17.33	52.20
	Relative error	0.11	0.61	0.02	0.16	0.01	0.45	0.00	0.05	0.03	0.00	BLLD	0.00	0.06	BLLD	0.08	0.05	0.12	0.13	0.11	0.07
ABK32		25.70	4.00	15.50	3.80	48.20	104.20	1.00	322.50	2.90	11.20	0.20	3.50	115.00	2.00	129.50	18.10	50.60	93.30	9.66	35.40
ABK33		26.70	4.30	15.00	3.70	46.90	104.80	1.00	319.00	3.00	11.00	0.30	3.50	109.00	3.00	128.90	18.10	50.20	92.90	9.41	35.60
	Relative error	0.03	0.05	0.02	0.02	0.01	0.00	0.00	0.01	0.02	0.01	0.28	0.00	0.04	0.28	0.00	0.00	0.01	0.00	0.02	0.00
ABK36		26.20	3.80	13.30	3.70	45.40	82.90	1.00	365.70	2.90	10.60	0.20	3.40	108.00	2.00	142.20	16.40	49.00	90.20	9.26	35.20
ABK37		25.80	3.40	13.90	3.60	41.10	82.40	1.00	353.00	2.50	9.40	0.50	3.10	102.00	2.00	133.40	15.80	44.10	81.70	8.44	31.60
	Relative error	0.01	0.04	0.03	0.02	0.07	0.00	0.00	0.02	0.10	0.08	0.61	0.07	0.03	0.00	0.05	0.03	0.07	0.07	0.07	0.06
ABK41		54.90	1.90	13.50	3.20	77.20	55.90	2.00	428.90	4.90	12.90	0.60	3.10	103.00	4.00	121.00	13.70	86.00	117.80	11.75	42.20
ABK42		55.80	1.90	12.70	2.90	83.20	64.60	1.00	456.70	5.20	13.30	0.60	3.00	106.00	3.00	118.30	13.90	70.10	127.10	12.71	45.60
	Relative error	0.01	0.00	0.04	0.07	0.05	0.10	0.47	0.04	0.04	0.02	0.00	0.02	0.02	0.20	0.02	0.01	0.04	0.05	0.06	0.05
ABK48		44.10	3.70	12.10	3.60	79.20	79.20	1.00	432.40	4.80	13.00	0.20	3.60	117.00	2.00	133.10	15.40	68.90	128.10	12.74	45.50
ABK47		43.50	3.80	12.20	3.40	78.70	84.50	< 1	419.60	5.00	13.00	0.20	3.60	123.00	2.00	132.70	15.90	69.50	126.80	12.78	45.10
	Relative error	0.01	0.02	0.01	0.04	0.00	0.05	BLLD	0.02	0.03	0.00	0.00	0.00	0.04	0.00	0.00	0.02	0.01	0.01	0.00	0.01
ABK49		40.20	4.20	14.10	5.00	104.80	92.50	2.00	687.30	6.40	16.20	0.50	4.70	156.00	2.00	199.90	19.40	84.30	171.80	17.58	64.30
ABK50		37.50	4.10	12.40	4.90	97.00	85.00	1.00	592.30	6.00	15.10	0.40	4.20	148.00	2.00	183.10	18.60	77.30	156.10	16.05	59.30
	Relative error	0.05	0.02	0.09	0.01	0.05	0.08	0.47	0.10	0.05	0.05	0.16	0.08	0.04	0.00	0.08	0.03	0.06	0.07	0.06	0.06
ABK53		84.70	0.80	5.80	3.60	215.60	35.60	1.00	780.00	15.60	39.00	0.10	4.90	90.00	3.00	135.10	15.10	200.20	386.50	37.00	127.80
ABK54		91.80	0.90	6.50	3.90	219.80	33.30	2.00	776.80	16.80	39.60	0.20	5.00	90.00	3.00	137.40	15.20	207.80	391.50	37.76	131.20
	Relative error	0.06	0.08	0.08	0.06	0.01	0.05	0.47	0.00	0.05	0.01	0.47	0.01	0.00	0.00	0.01	0.00	0.03	0.01	0.01	0.02
ABK59		89.40	1.00	7.40	5.50	253.80	34.80	2.00	736.60	23.40	37.70	< .1	6.00	145.00	2.00	202.20	13.10	187.30	322.80	30.06	98.20
ABK60		90.40	1.00	8.00	5.50	268.50	37.50	3.00	809.70	22.10	37.30	0.50	6.00	136.00	1.00	201.90	14.00	202.80	344.50	32.05	101.50
	Relative error	0.01	0.00	0.06	0.00	0.04	0.05	0.28	0.07	0.04	0.01	BLLD	0.00	0.05	0.47	0.00	0.05	0.06	0.05	0.05	0.02
ABK69		72.00	0.70	5.80	4.40	223.90	14.20	2.00	775.30	13.90	31.30	< .1	3.90	104.00	< 1	172.70	9.90	133.60	230.30	21.80	72.50
ABK70		75.90	0.80	6.70	4.70	220.70	14.90	2.00	803.00	12.20	31.30	< .1	4.10	98.00	< 1	171.70	10.40	140.00	236.20	22.57	72.00
	Relative error	0.04	0.09	0.10	0.05	0.01	0.03	0.00	0.02	0.09	0.00	BLLD	0.04	0.04	BLLD	0.00	0.03	0.03	0.02	0.02	0.00
Avg. relative error (%)		**3.51**	**9.11**	**6.00**	**4.89**	**3.23**	**8.58**	**21.68**	**3.79**	**5.27**	**2.69**	**25.29**	**2.33**	**3.31**	**13.68**	**2.76**	**2.75**	**4.80**	**4.78**	**4.55**	**3.84**

Duplicate Pairs: Trace Elements (INNA)

Sample No.		Sm ppm	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Ho ppm	Er ppm	Tm ppm	Yb ppm	Lu ppm
ABK12		12.10	3.11	5.58	0.61	3.41	0.39	1.17	0.10	0.58	0.07
ABK13		13.00	3.33	6.33	0.68	3.66	0.44	1.33	0.10	0.63	0.07
	Relative error	0.05	0.05	0.09	0.06	0.05	0.09	0.09	0.00	0.06	0.00
ABK17		6.10	1.50	2.87	0.37	1.98	0.26	0.82	0.08	0.49	0.07
ABK18		5.40	1.39	2.74	0.32	1.92	0.25	0.74	0.06	0.47	0.07
	Relative error	0.09	0.05	0.03	0.10	0.02	0.03	0.07	0.20	0.03	0.00
ABK32		5.40	1.48	4.09	0.58	3.34	0.65	2.02	0.27	1.71	0.25
ABK33		5.50	1.40	4.12	0.55	3.32	0.67	2.01	0.28	1.74	0.27
	Relative error	0.01	0.04	0.01	0.01	0.00	0.02	0.00	0.03	0.01	0.05
ABK36		5.30	1.18	3.89	0.50	3.09	0.59	1.85	0.23	1.60	0.26
ABK37		4.80	1.14	3.68	0.48	2.96	0.58	1.76	0.24	1.50	0.23
	Relative error	0.07	0.02	0.04	0.03	0.03	0.01	0.04	0.03	0.05	0.09
ABK41		6.00	1.53	3.71	0.51	2.68	0.52	1.44	0.22	1.25	0.20
ABK42		6.00	1.55	4.03	0.51	3.02	0.52	1.59	0.19	1.27	0.17
	Relative error	0.00	0.01	0.06	0.00	0.08	0.00	0.07	0.10	0.01	0.11
ABK46		6.20	1.60	4.04	0.56	3.17	0.54	1.80	0.22	1.43	0.20
ABK47		6.70	1.68	4.23	0.53	3.14	0.57	1.76	0.21	1.45	0.21
	Relative error	0.05	0.03	0.03	0.04	0.01	0.04	0.02	0.03	0.01	0.03
ABK49		9.20	2.30	5.83	0.75	4.11	0.75	2.15	0.25	1.69	0.23
ABK50		8.80	2.19	5.37	0.69	3.90	0.71	2.24	0.25	1.65	0.25
	Relative error	0.03	0.03	0.03	0.06	0.04	0.04	0.03	0.00	0.02	0.06
ABK53		14.40	3.70	6.66	0.74	4.34	0.55	1.72	0.18	0.94	0.12
ABK54		14.80	3.76	7.09	0.83	4.35	0.58	1.74	0.15	0.99	0.13
	Relative error	0.02	0.01	0.04	0.08	0.00	0.04	0.01	0.05	0.04	0.06
ABK59		11.70	2.83	4.88	0.63	3.98	0.53	1.33	0.12	0.88	0.12
ABK60		12.00	2.95	5.22	0.65	4.08	0.57	1.46	0.13	0.81	0.11
	Relative error	0.02	0.03	0.05	0.02	0.02	0.05	0.07	0.06	0.06	0.06
ABK69		8.40	2.11	4.20	0.49	3.06	0.42	1.11	0.10	0.71	0.11
ABK70		8.70	2.08	4.04	0.52	2.90	0.42	1.07	0.09	0.71	0.10
	Relative error	0.02	0.01	0.03	0.04	0.04	0.00	0.03	0.07	0.00	0.07
Avg. relative error (%)		**3.68**	**2.95**	**4.18**	**4.64**	**2.92**	**3.12**	**4.17**	**5.72**	**2.79**	**5.34**

Duplicate Pairs: Trace Elements (ICP)

Sample No.		Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ni ppm	As ppm	Cd ppm	Sb ppm	Bi ppm
ABK12		1.00	32.00	8.00	53.00	1279.00	< 2	< .2	< .5	< .5
ABK13		< 1	32.00	7.00	54.00	1280.00	< 2	< .2	< .5	< .5
	Relative error	BLLD	0.00	0.09	0.01	0.00	BLLD	BLLD	BLLD	BLLD
ABK17		1.00	22.00	11.00	54.00	1077.00	< 2	0.20	< .5	0.70
ABK18		1.00	21.00	8.00	54.00	1191.00	< 2	< .2	< .5	1.10
	Relative error	0.00	0.03	0.22	0.00	0.07	BLLD	BLLD	BLLD	0.31
ABK32		1.00	37.00	11.00	74.00	219.00	7.00	0.60	< .5	< .5
ABK33		1.00	38.00	11.00	75.00	222.00	8.00	0.60	< .5	0.50
	Relative error	0.00	0.02	0.00	0.01	0.01	0.09	0.00	BLLD	BLLD
ABK36		1.00	36.00	9.00	72.00	223.00	5.00	0.60	< .5	< .5
ABK37		1.00	36.00	10.00	71.00	210.00	6.00	0.60	< .5	0.50
	Relative error	0.00	0.00	0.07	0.01	0.04	0.13	0.00	BLLD	BLLD
ABK41		3.00	42.00	9.00	65.00	732.00	5.00	0.40	< .5	< .5
ABK42		4.00	43.00	9.00	66.00	730.00	5.00	0.50	< .5	< .5
	Relative error	0.20	0.02	0.00	0.01	0.00	0.00	0.16	BLLD	BLLD
ABK46		1.00	46.00	11.00	70.00	510.00	6.00	0.70	< .5	< .5
ABK47		< 1	48.00	10.00	71.00	494.00	5.00	0.70	< .5	< .5
	Relative error	BLLD	0.03	0.07	0.01	0.02	0.13	0.00	BLLD	BLLD
ABK49		1.00	52.00	13.00	77.00	350.00	6.00	0.60	< .5	0.50
ABK50		1.00	49.00	13.00	78.00	335.00	7.00	0.70	< .5	< .5
	Relative error	0.00	0.06	0.00	0.01	0.03	0.11	0.11	BLLD	BLLD
ABK53		2.00	45.00	12.00	62.00	787.00	< 2	0.20	0.60	< .5
ABK54		2.00	45.00	11.00	65.00	844.00	< 2	< .2	< .5	< .5
	Relative error	0.00	0.00	0.06	0.03	0.05	BLLD	BLLD	BLLD	BLLD
ABK59		2.00	65.00	11.00	73.00	636.00	2.00	< .2	< .5	< .5
ABK60		2.00	67.00	11.00	80.00	613.00	< 2	< .2	< .5	0.50
	Relative error	0.00	0.02	0.00	0.06	0.03	BLLD	BLLD	BLLD	BLLD
ABK69		2.00	48.00	9.00	55.00	515.00	< 2	< .2	1.40	1.00
ABK70		1.00	47.00	8.00	55.00	513.00	< 2	< .2	1.70	1.00
	Relative error	0.00	0.01	0.08	0.00	0.00	BLLD	BLLD	0.14	0.00
Avg. relative error (%)		**0.00**	**0.04**	**0.04**	**0.01**	**0.07**	**9.20**	**5.32**	**13.89**	**15.71**

BLLD* Below lower limit of detection
Buffalo Head Hills
Mountain Lake
Birch Mountains

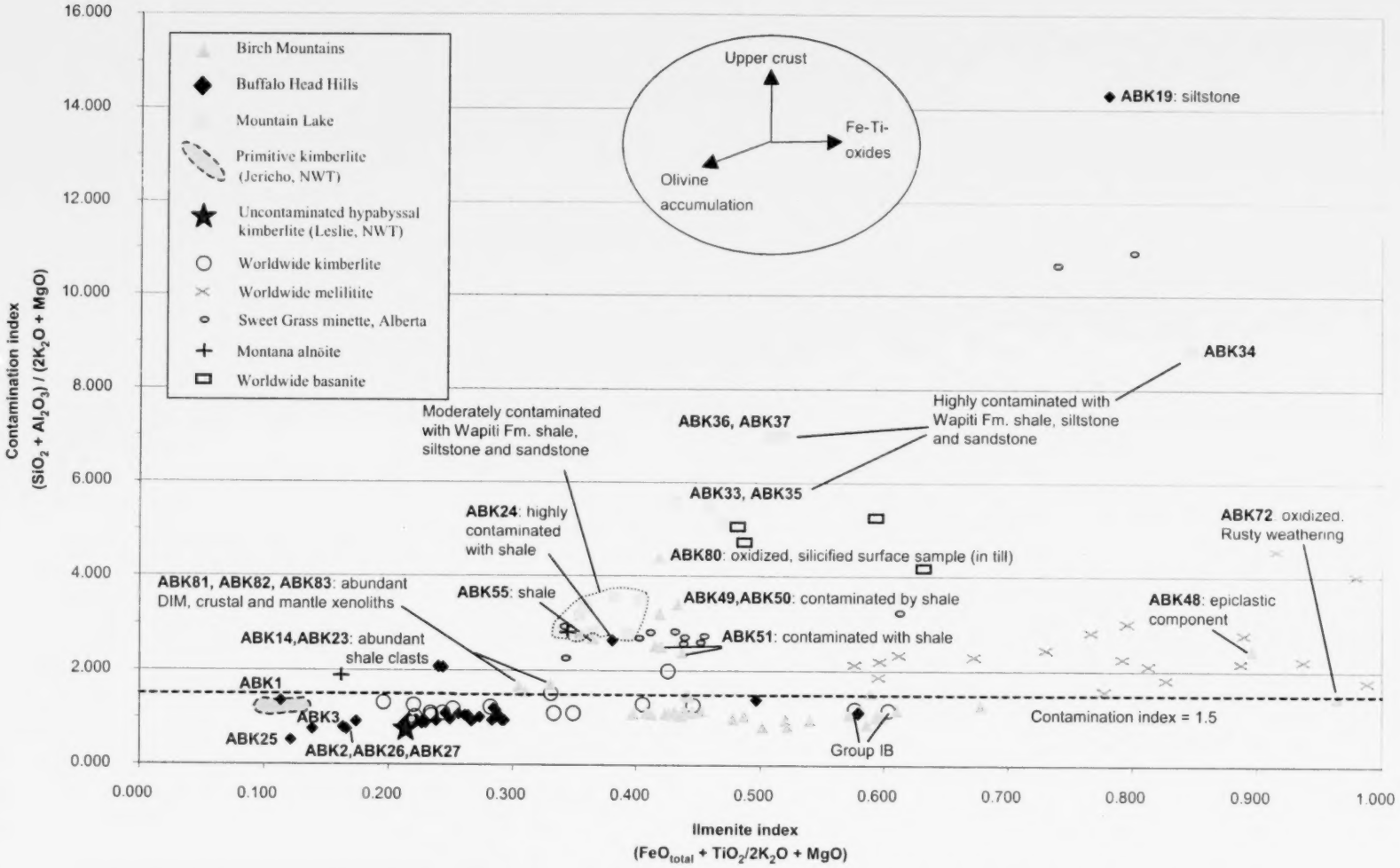

Figure 2. Plot of contamination index of Clement (1982) versus ilmenite index of Taylor et al. (1994) for Alberta kimberlitic whole-rock compositions. Contaminated rocks (C.I. >1.5) are labelled and include macroscopic observations. Dashed line represents a C.I. of 1.5; vectors show trends for kimberlite contamination by granitic and siliceous crustal rocks, Fe- and Ti-oxide (ilmenite) accumulation, and olivine accumulation (Taylor et al., 1994). See section 2.4 in text for sources of comparative data.

- The Mountain Lake samples are characterized by high C.I. values (2.7 to 8.8), characteristic of kimberlite with upper crust contamination, and moderately high Ilm.I. (0.34 to 0.85). These characteristics are also shared with minette and basanite.

- The Buffalo Head Hills samples generally have low C.I. (<1.5) and Ilm.I. (<0.3), and 60% (19 samples) plot close to the primitive kimberlite magma from the Northwest Territories (Price et al., 2000; Berg and Carlson, 1998).

- The Birch Mountains samples generally have relatively low C.I. (<1.5) and high Ilm.I. (>4.0), the latter consistent with the observed relatively high bulk-rock TiO_2 contents.

Samples with a C.I. >1.5 include 1) ABK31 to ABK47 (all samples, Mountain Lake); 2) ABK14, ABK19, ABK23 and ABK24 (Buffalo Head Hills); and 3) ABK48, ABK49, ABK50, ABK51, ABK55, ABK81, ABK82 and ABK83 (Birch Mountains). Most of these samples contain macroscopically obvious sources of contamination, including shale, siltstone and sandstone, and/or oxidized, highly weathered material. The generalized physical observations of samples with a C.I. >1.5 are included on Figure 2.

Sweet Grass minette and worldwide basanite rocks roughly coincide with the Mountain Lake pipes. In contrast to the Buffalo Head Hills and Birch Mountains, where only a few samples plot as highly contaminated, the Mountain Lake rocks plot in two high-C.I. groups, which may indicate fairly homogeneous major-element chemistry. These observations suggest that the differences in composition between the Mountain Lake and the Buffalo Head Hills and Birch Mountains pipes are more likely a function of the ultramafic magma type rather than solely a result of more extensive crustal contamination in the Mountain Lake pipe. This hypothesis is discussed in more detail in section 3.2.

Clement (1982) and Mitchell (1986) suggested that contamination increases the whole-rock concentrations of SiO_2, Al_2O_3 and Na_2O in kimberlite. Mitchell (1986) concluded that <35 wt. % SiO_2 and <5 wt. % Al_2O_3 are indicative of contamination-free kimberlite, and that mixing lines of various contaminants and weathering products could explain variations in kimberlite chemistry. Figure 3 (Al_2O_3 vs. SiO_2) shows that the majority of the Buffalo Head Hills samples (90%) and Birch Mountains samples (75%) plot in the contamination-free field, but none of the Mountain Lake samples plot in the contamination-free field. Berg (1998) proposed that 2.2% Al_2O_3 be used as a maximum for contamination-free nonmicaceous kimberlite. Berg's cutoff would limit contamination-free kimberlite in Alberta to the Buffalo Head Hills.

Seven samples, including ABK1, ABK2, ABK3, ABK8, ABK11, ABK26 and ABK27, contain lower Al_2O_3 and higher SiO_2 than the Northwest Territories primitive kimberlite. The negative trend of these samples in Figure 3 corresponds to the serpentine weathering line of Mitchell (1986). The bleached, green-yellow appearance of some of these samples favours serpentine alteration.

Based on geochemistry and examination of hand specimens and thin sections, mixing lines can be defined between kimberlite and carbonate and serpentine, which are alteration products of the kimberlite, and contamination from host rocks (shale, siltstone and sandstone). These mixing lines are included on Figure 3 and may be used to assess future kimberlitic rock discoveries in northern Alberta.

3.2 Compositional Variation Between Magmas

For comparison, average compositions of kimberlite olivine/madupitic lamproite, melilitite, Sweet Grass olivine minette and basanite are presented in Table 2. Mitchell (1986) cautioned that the 'representative'

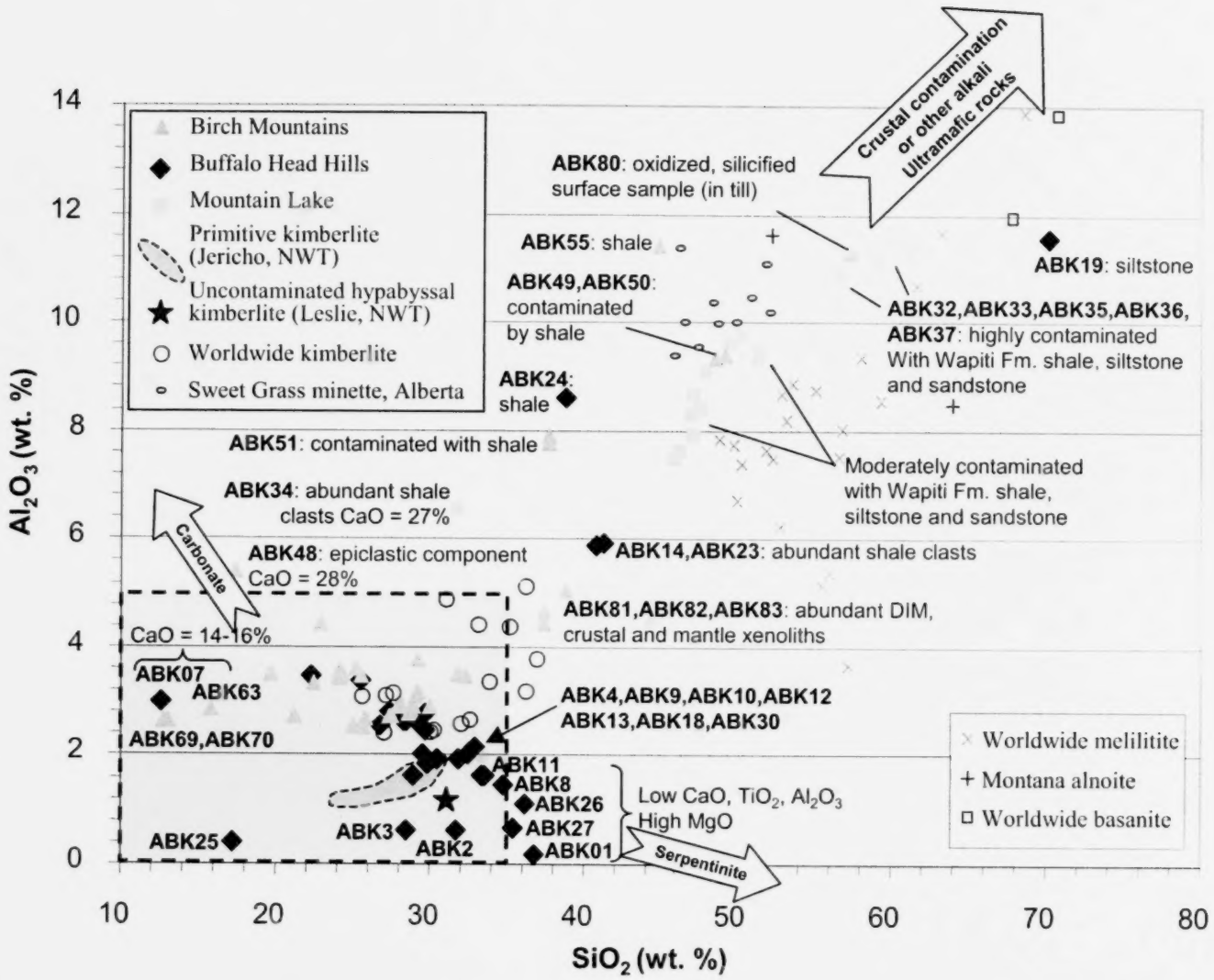

Figure 3. Whole-rock Al_2O_3 versus SiO_2 for kimberlitic samples from Alberta. Arrows indicate alteration (serpentinization and carbonatization) and crustal contamination (shale, siltstone, sandstone and felsic rocks) vectors for northern Alberta. The crustal-contamination vectors that plot well outside the contamination-free kimberlite (shaded box; Mitchell, 1986) are based on macroscopic observations or generalized compositions of northern Alberta Cretaceous sedimentary rocks (Dufresne et al., in press). See section 2.4 in text for sources of comparative data. Abbreviation: DIM, diamond-indicator minerals.

Table 2. Comparison of selected major elements in Alberta kimberlitic rocks with average kimberlite, olivine/madupitic lamproite, olivine melilitite, olivine minette and basanite.

	Average kimberlite[1]		Average lamproite[2]		Average	Average Sweet	Average	Mountain Lake			Buffalo Head Hills			Birch Mountains		
Element	Min.	Max.	Min.	Max	melilitite[3]	Grass minette[4]	Basanite[5]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
SiO_2	25.50	36.40	40.00	51.00	36.21	49.76	44.30	31.96	61.61	51.35	12.66	70.12	31.60	12.76	57.39	29.25
Al_2O_3	2.50	5.10	3.00	9.00	8.03	10.72	14.70	6.56	11.49	9.46	0.17	11.53	2.66	2.50	11.42	4.32
Fe_2O_3	3.90	6.78	1.85	8.78	14.50	8.71	3.94	3.62	7.78	6.21	3.47	9.51	7.66	3.62	14.98	8.92
MgO	17.00	28.60	12.00	28.00	15.18	9.91	8.54	2.45	16.74	11.51	1.90	44.94	30.34	4.51	29.60	22.46
CaO	7.60	21.37	4.00	13.00	14.40	7.70	10.19	2.67	27.55	5.09	0.75	23.09	7.38	1.78	27.97	9.82
Na_2O	0.12	0.48	0.29	1.42	2.25	1.68	3.55	0.92	2.66	1.84	0.01	2.38	0.19	0.03	3.00	0.33
K_2O	0.34	2.10	3.00	9.00	1.41	5.25	1.96	1.03	3.10	2.22	0.06	3.86	0.54	0.04	4.62	0.91
TiO_2	1.20	3.40	1.00	5.00	3.96	0.97	2.51	0.56	0.92	0.83	0.01	1.44	0.71	0.54	4.76	2.73
P_2O_5	0.70	1.10	1.00	3.00	1.12	1.00	0.74	0.20	0.44	0.29	0.12	0.96	0.47	0.27	0.91	0.54
MnO	0.10	0.19	0.10	0.13	0.22	0.14	0.16	0.08	0.22	0.11	0.03	0.19	0.13	0.05	0.32	0.16
Cr_2O_3	0.11	0.25	N/A*	N/A	N/A	N/A	N/A	0.05	0.14	0.01	0.01	0.22	0.14	0.02	0.21	0.12
Na_2O/K_2O	0.35	0.23	0.10	0.16	1.60	0.32	1.81	0.89	0.86	0.83	0.17	0.62	0.35	0.75	0.65	0.36
Peralkalinity index[6]	0.23	0.60	1.24	1.34	0.65	0.79	0.54	0.40	0.67	0.57	0.48	0.70	0.34	0.04	0.87	0.35
Niggli K[7]	0.65	0.74	0.87	0.81	0.29	0.67	0.27	0.42	0.43	0.44	0.80	0.52	0.65	0.47	0.50	0.64
Niggli mg[8]	0.85	0.85	0.89	0.81	0.58	0.60	0.74	0.47	0.74	0.71	0.42	0.86	0.84	0.62	0.72	0.77
Mg#[9]	89.62	89.31	92.78	86.33	67.46	69.26	81.11	57.27	80.99	78.59	52.02	90.35	88.69	71.16	79.65	83.30

1 Representative average composition of kimberlite (Mitchell, 1986)

2 Geochemical criteria for olivine/madupitic lamproite (Mitchell and Bergman (1991). Included are the:
- composition of Fe_2O_3, Na_2O and MnO for madupitic lamproite, Prairie Creek (Scott Smith and Skinner, 1994)
- composition of Fe_2O_3, Na_2O and MnO from average of 52 olivine lamproites (Scott, 1979)

3 Average worldwide composition for olivine melilitite (Wilson et al., 1995; Rogers et al., 1992)

4 Average composition of Sweet Grass, Alberta olivine minette (Kjarsgaard, 1994; Buhlmann et al., 2000)

5 Average worldwide basanite (Le Maitre, 1976)

6 Peralkalinity Index = molar $(K_2O+Na_2O)/Al_2O_3$

7 Niggli K = molar $K_2O/(K_2O+Na_2O)$

8 Niggli mg = molar $MgO/(MgO+FeO_{total}+Fe_2O_3+MnO)$

9 Mg# = $100*MgO/(MgO+FeO_{total})$

* N/A = not available

average composition of kimberlite is derived from global data sets that were not assessed for the amount of alteration and contamination. The same cautionary note applies to other rock types used for comparative purposes.

3.2.1 Mountain Lake

The Mountain Lake samples have very different major-element chemistries compared to the Buffalo Head Hills and Birch Mountains samples (Figure 4; Table 2). Generally, the Mountain Lake samples contain high SiO_2 (average 51.4 wt. %), high MgO (average 11.5 wt.% with Mg# of 78.6), low Al_2O_3 (average 9.5 wt. %) and relatively low alkalis (average 2.2 wt. % K_2O and 1.8 wt. % Na_2O). The Mountain Lake rocks have higher SiO_2, Al_2O_3, Na_2O, K_2O, Na_2O/K_2O ratio (0.83); higher peralkalinity index (average molar $[K_2O+Na_2O]/Al_2O_3 = 0.57$); and lower MgO, Niggli K (average molar $K_2O/[K_2O+Na_2O] = 0.44$) and Niggli mg (average molar $MgO/[MgO+FeO+ Fe_2O_3+MnO] = 0.71$) compared to the Buffalo Head Hills and Birch Mountains samples.

Contamination problems aside, the major-element chemistry of the Mountain Lake samples is not consistent with either kimberlite (25 to 35 wt. % SiO_2; <5 wt. % Al_2O_3; Na_2O/K_2O ratio <0.5) or lamproite (peralkaline index >0.7, Niggli K >0.8 and Niggli mg >0.8). This finding is consistent with that based on petrographic examination by Leckie et al. (1997), who concluded that the Mountain Lake pipe was not a kimberlite. Therefore, the Mountain Lake rocks may be 1) classified as a magma type other than kimberlite or lamproite; 2) influenced by posteruption alteration of a type not seen elsewhere; 3) highly contaminated by country rocks; and/or 4) any combination of the above.

The major-element chemistry of the Mountain Lake samples shows some similarity to those of the Sweet Grass minette and worldwide basanite (Table 2). For example, Appendix 4A shows a negative correlation in both the Mountain Lake samples and the Sweet Grass minette for SiO_2 versus MgO and Al_2O_3 versus MgO, and a positive correlation for TiO_2 versus Fe_2O_3. However, significant differences exist in K_2O, Fe_2O_3 and P_2O_5. For example, average values for the Mountain Lake pipes and the Sweet Grass minette are 2.22 versus 5.25 wt. % K_2O, 6.21 versus 8.71 wt. % Fe_2O_3 and 0.29 versus 1.0 wt. % P_2O_5, respectively. Despite these differences, there are parallel trends for K_2O versus MgO and K_2O versus Fe_2O_3.

With their high SiO_2 contents and peralkalinity indices, the Mountain Lake samples ABK31 to ABK33 and ABK35 to ABK47 plot in the field of Roman Province type (RPT) potassic lavas (Figure 5), which Mitchell and Bergman (1991) have suggested characterize most minettes worldwide. The data from basanite, Sweet Grass minette and Montana alnöite (Hearn, 1986) also plot in the RPT field, suggesting similar petrogenesis. Sample ABK34 has a lower SiO_2 content (31.96 wt. %) and plots below the RPT field near kimberlite and melilitite.

A K_2O versus Na_2O diagram (Figure 6A) discriminates clearly between kimberlite and the Mountain Lake samples, showing the strongly potassic nature of kimberlite. The lack of overlap between kimberlite and the more sodic Mountain Lake rocks must reflect major mineralogical differences between their mantle sources, degree of melting or subsequent fractionation. A 1:1 K_2O versus Na_2O line has been used by Le Bas (1989) to divide potassic rocks (e.g., lamprophyric) from nonpotassic rocks (e.g., melilitite, nephelinite). The majority of the Mountain Lake samples plot on the potassic side of this discrimination line.

The Mountain Lake samples were also plotted on the total alkalis versus SiO_2 diagram (TAS classification, Figure 6B) and on the $CaO+Na_2O+K_2O$ versus $SiO_2+Al_2O_3$ diagrams (Figure 6C) of Le Bas (1989) and Le Maitre (1989) to differentiate between similar potassic rocks. The Mountain Lake sam-

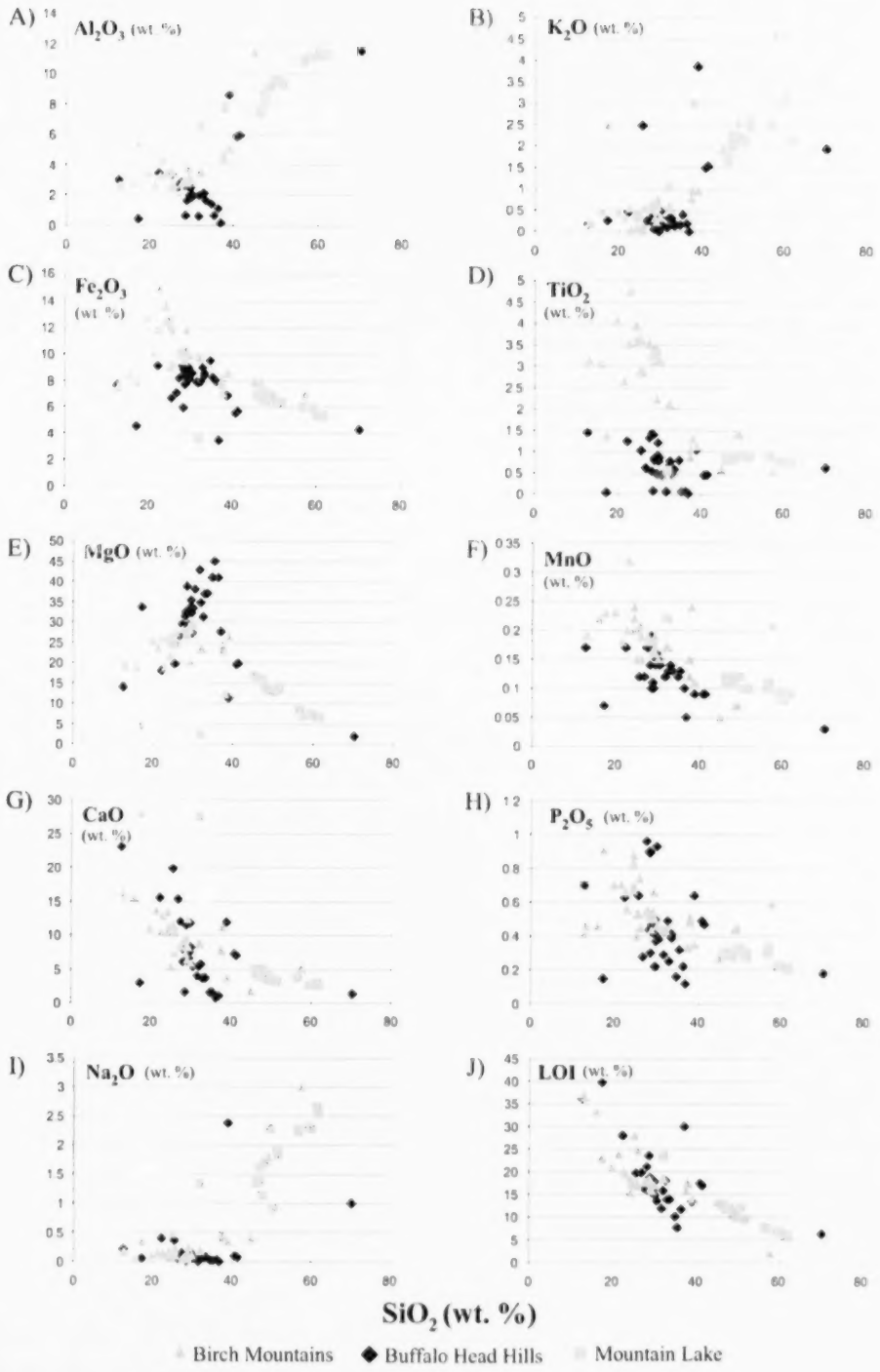

Figure 4. Major-element whole-rock variation diagrams with SiO_2 for kimberlitic rocks from Alberta.

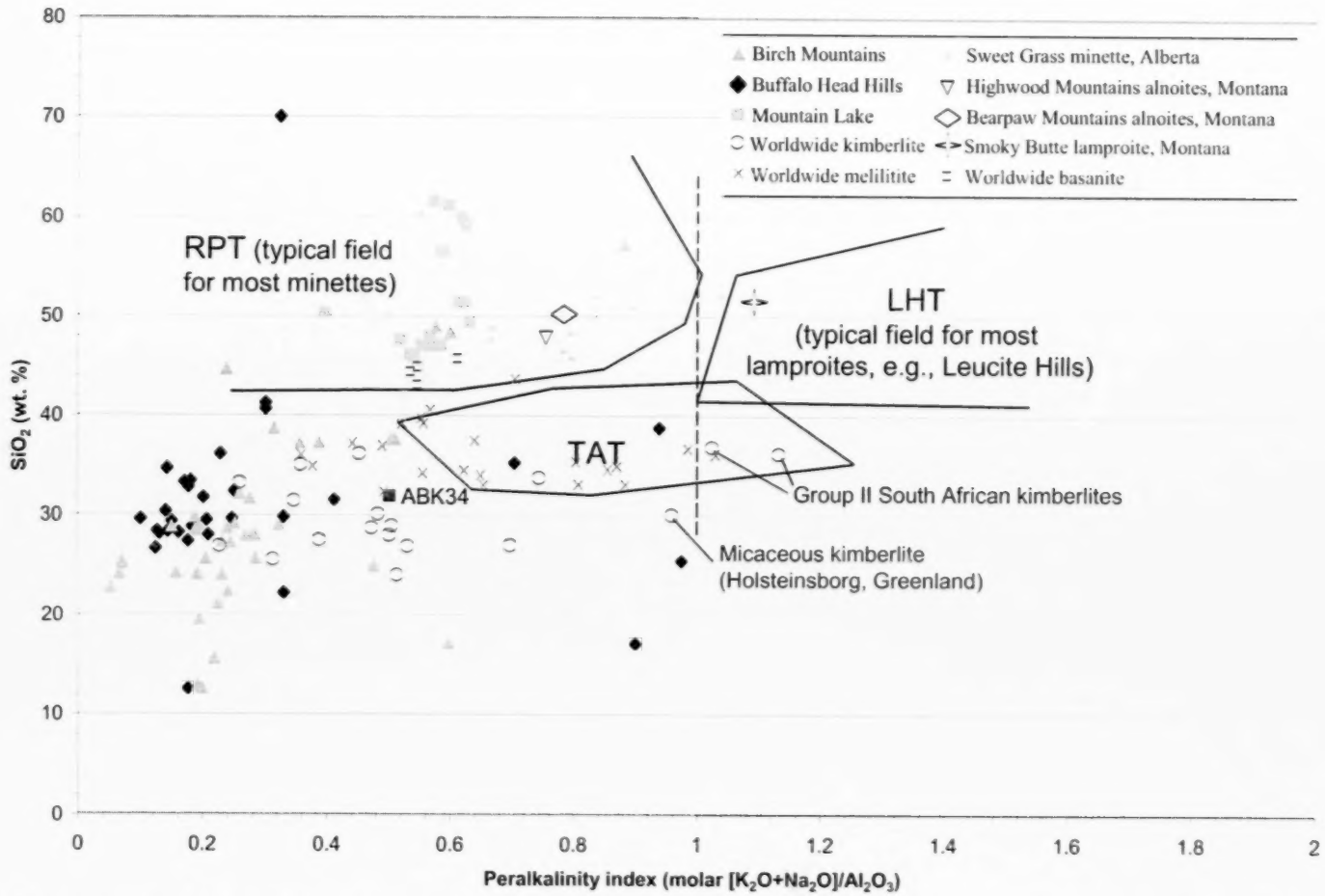

Figure 5. SiO_2 versus peralkalinity index (molar $[K_2O+Na_2O]/Al_2O_3$) for Alberta kimberlitic whole-rock compositions. Dashed line represents a peralkalinity value of 1.0. Solid vectors or polygons represent the three groups of potassic lavas recognized by Barton (1979): RPT, Roman Province type lavas; LHT, Leucite Hills type lavas; TAT, Toro-Ankole type lavas. See section 2.4 in text for sources of comparative data.

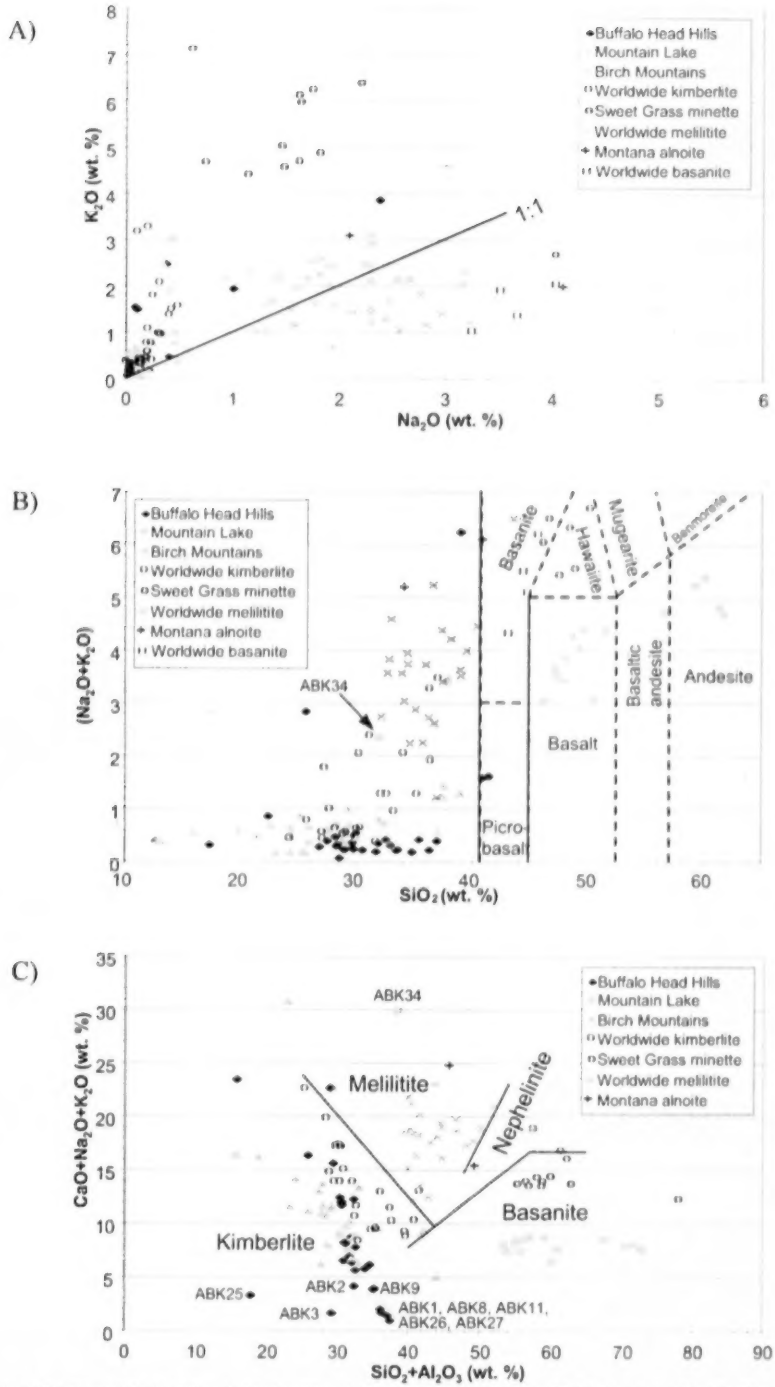

Figure 6. Alkali classification plots for Alberta kimberlitic whole-rock compositions: A) K_2O versus Na_2O; B) total alkalis versus SiO_2 (TAS classification); C) $CaO+Na_2O+K_2O$) versus $SiO_2+Al_2O_3$. See section 2.4 in text for sources of comparative data.

ples plot in the field for basalt to andesite on Figure 6B and in the field for basanite on Figure 6C. These plots clearly show the difference between the Mountain Lake samples and those from the Buffalo Head Hills and Birch Mountains. Sample ABK34 from Mountain Lake plots in the field of melilitite on Figure 6C. It is not presently known why sample ABK34 contains such a different chemistry (e.g., lower SiO_2 and MgO, higher CaO) than the rest of the Mountain Lake samples.

Possible contamination of the Mountain Lake samples must be evaluated before any conclusions can be drawn regarding their original chemistry. The rocks are highly altered to smectitic minerals (montmorillonite) and the olivine is completely pseudomorphed by serpentine or carbonate. Formation of clay minerals, serpentinization of olivine and the introduction of Cretaceous sedimentary rocks will increase SiO_2 and Al_2O_3 contents. Berg (1998) proposed that a positive trend between Na_2O and SiO_2 is likely related to high sodium in shale, postemplacement water circulation, or the presence of pectolite and Ti-rich acmite. The positive trends of Al_2O_3, K_2O and Na_2O versus SiO_2 (Figure 4A, B and I) and a high contamination index (>2.7) suggest that the Mountain Lake samples may have a high degree of contamination from addition of Cretaceous Wapiti Formation shale, siltstone and sandstone. This hypothesis is further supported by the negative correlation of MgO versus SiO_2. Such a negative correlation was interpreted by Berg (1988) as being the result of contamination by country rock (Figure 4E). Finally, extensive contamination might be expected, since Leckie et al. (1997) reported that the Mountain Lake pipes were syndepositionally emplaced with the mid-Cretaceous Wapiti Formation sedimentary rocks and is therefore contaminated by variable amounts of quartz and feldspathic minerals. We suspect that additional quartz would influence the classification of the Mountain Lake kimberlitic rocks. For example, we predict that, if the rocks were not contaminated by quartz, the samples would plot to the left of basalt on the TAS diagram (Figure 6B) and more likely resemble a basanite.

In summary, the major-element chemistry of the Mountain Lake rocks is not consistent with this rock type being kimberlite. However, the degree of contamination and hybrid geochemical affinities also make it difficult to classify the Mountain Lake pipes on the basis of major-element chemistry. Depending on the combination of major elements used for interpretation, the Mountain Lake rocks have affinities that are similar to basanite, minette and alnöite, further illustrating the complex nature of the Mountain Lake pipes. Nevertheless, the similarity of Mountain Lake to the Sweet Grass minette, Montana alnöite and other alkali rock types (e.g., basanite) will be explored throughout this report.

3.2.2 Buffalo Head Hills

Samples from the Buffalo Head Hills are the least contaminated samples in this data set (Figures 2 and 3). They have low SiO_2 (average 31.60 wt. %), high MgO (average 30.34 wt. %; Mg# averages 88.69 and is up to 90.35), very low Al_2O_3 (average 2.66 wt. %) and a low Na_2O/K_2O ratio (0.35). When compared to worldwide kimberlite averages (Table 2), the pipes in the Buffalo Head Hills region may be described as classic Group I kimberlite.

Four samples from the Buffalo Head Hills are contaminated, based on macroscopic observations, high SiO_2 content (>38 wt. %) and high C.I. (>1.5). Samples ABK14, ABK23 and ABK24 are characterized by variable amounts of country rock (dominantly shale). Sample ABK19 represents the rock with the highest degree of contamination in this dataset; it is contaminated by siltstone and has very high SiO_2 (70.12%) and C.I. (14.3).

A steep, positive MgO versus SiO_2 correlation (Figure 4E) characterizes the Buffalo Head Hills samples. Berg (1998) observed, from the bulk geochemistry and petrography of 70 South African kimberlites, that the positive correlation between SiO_2 and MgO, similar to the Buffalo Head Hills, is typically associated with hypabyssal, primitive kimberlite. A primitive magma source for the Buffalo Head Hills samples is

supported by their proximity to primitive kimberlite from the Northwest Territories.

A small group of between six and eight samples (samples ABK1, ABK2, ABK3, ABK8, ABK11, ABK25, ABK26 and ABK27) cluster together on several bivariate plots (e.g., Figures 2, 3 and 6C). These samples contain the lowest values of Al_2O_3 (1.11 wt. %), TiO_2 (0.08 wt. %) and CaO (3.97 wt. %), and the highest values of MgO (up to 44.94 wt. %) and Cr_2O_3 (up to 0.221 wt. %) of the Alberta kimberlitic samples. In Figure 2, they plot close to samples from the Jericho kimberlite (Northwest Territories) and a sample from the Leslie kimberlite (Northwest Territories) that are considered by Price et al. (2000) and Berg and Carlson (1998), respectively, to represent hypabyssal kimberlite that that is either minimally contaminated or uncontaminated. Conversely, a negative trend for samples ABK1, ABK2, ABK3, ABK26 and ABK27 on the plot of Al_2O_3 versus SiO_2 (Figure 3) suggests that these samples are moderately to highly serpentinized and, instead, samples ABK4, ABK9, ABK10, ABK12, ABK13, ABK18 and ABK30 plot close to Northwest Territories primitive kimberlite. The variations between these two groups of samples from the Buffalo Head Hills will be discussed throughout this report.

We conclude that the Buffalo Head Hills represent the most primitive Group I kimberlite phase in this dataset based on their

- major-element chemistry (low SiO_2, high MgO and Mg#, and very low Al_2O_3);
- similarity between the Buffalo Head Hills kimberlites and primitive kimberlite from the Jericho and Leslie pipes (Northwest Territories); and
- positive correlation between MgO and SiO_2.

3.2.3 Birch Mountains

Major-element geochemistry from the Birch Mountains pipes (Table 2) indicates that they have low SiO_2 (average 29 wt. %), low Al_2O_3 (average 4 wt. %) and low Na_2O/K_2O ratios (0.36) .

Eight samples from the Birch Mountains are contaminated, based on macroscopic observations and high SiO_2 content (>35 wt. %) and high C.I. (>1.5). Samples ABK49, ABK50 (duplicate of ABK49), ABK51 and ABK55 are characterized by variable amounts of country rock (dominantly shale). Sample ABK80 is highly weathered and was discovered in surface till, raising the possibility that it is not even be locally derived. Samples ABK81, ABK82 and ABK83 from the Kendu pipe contain higher SiO_2 (37–39 wt. %), but also have the highest Mg# (85–86), lowest TiO_2 (0.88–1.13) and Ilm.I. (0.305–0.331) of the Birch Mountains samples. Macroscopic observations of the Kendu samples suggest that the kimberlite is contaminated by mantle xenoliths and macrocrysts and crustal xenoliths, which may account for the higher SiO_2 content.

Mitchell (1986) suggested that differentiation of kimberlite magma by olivine fractionation will lead to a residual melt depleted in MgO and SiO_2, but enriched in CaO, TiO_2 and volatiles. Figure 4 and Appendix 4B show plots of various oxides versus SiO_2. Compared to samples from the Buffalo Head Hills, samples from the Birch Mountains have lower contents of MgO and SiO_2 and higher contents of Fe_2O_3, MnO, CaO, P_2O_5 and TiO_2. Despite a high Ilm.I. and high TiO_2 (typically >2 wt. % and averaging 2.73 wt. %), which may reflect the effect of an accumulation of ilmenite on bulk geochemistry, the major-element geochemistry of the Birch Mountains pipes is consistent with that of evolved kimberlite.

In summary, plots that use major-element compositions to differentiate contaminated from uncontaminated kimberlite divide Alberta ultramafic rocks into three groups that are also defined by their geo-

graphic areas. In broad terms, these include

- the Mountain Lake samples, which are not kimberlite but a hybrid alkali potassic ultramafic rock that is contaminated by Wapiti Formation shale, siltstone and sandstone;

- the Buffalo Head Hills samples, which are more primitive Group I kimberlite samples with low to minimal contamination; and

- the evolved, Fe- and Ti-rich kimberlite of the Birch Mountains samples.

3.2.4 Major-Element Comparisons Between the Buffalo Head Hills and Birch Mountains, and with Kimberlites Worldwide

In general, the Buffalo Head Hills and Birch Mountains samples have higher concentrations of Fe_2O_3 and slightly lower concentrations of Cr_2O_3 than worldwide kimberlite averages (Table 2, Appendices 4A and B). The Birch Mountains contain significantly higher TiO_2 concentrations. With the exception of higher Fe_2O_3 and lower P_2O_5, the major-element chemistry of samples from the Birch Mountains pipes falls within the field of average kimberlite (Table 2). Compared to average kimberlite (Table 2), however, samples from the Buffalo Head Hills contain slightly higher Fe_2O_3 and MgO, and slightly lower CaO, TiO_2 and P_2O_5. Nevertheless, on the basis of major-element geochemistry, it can be concluded that samples from the Buffalo Head Hills and Birch Mountains are kimberlitic in origin.

In Figures 2 and 3, the Buffalo Head Hills and Birch Mountains samples coincide with other kimberlites. Some of the Birch Mountains rocks with higher Ilm.I coincide with reported composition for Group IB South Africa kimberlites. The majority of the Buffalo Head Hills samples coincide with a grouping of worldwide kimberlite (low C.I. and Ilm.I. between 0.2 and 0.3). A large number of Buffalo Head Hills samples (e.g., ABK1 to ABK04, ABK8 to ABK13, ABK18, ABK25 to ABK27 and ABK30) plot close to primitive kimberlites from Northwest Territories

On plots of Mg# versus SiO_2, K_2O and TiO_2 (Figure 7), the Buffalo Head Hills, Mountain Lake and Birch Mountains samples are compared to representative fields for South African Group I and Group II kimberlites (Clement, 1982; Smith et al., 1985). Although there is significant overlap between the two South African groups, the high-Mg# Buffalo Head Hills samples and high-TiO_2 Birch Mountains samples plot in the nonmicaceous Group I kimberlite field. The Buffalo Head Hills samples plot close to the primitive kimberlite magma from the Jericho pipe (Northwest Territories).

Mountain Lake samples with high Mg# plot in the field of nonmicaceous Group I kimberlite on the diagram of Mg# versus K_2O (Figure 7B) and outside the kimberlite fields for Mg# versus SiO_2 and TiO_2 (Figures 7A and C, respectively). As discussed previously, the Mountain Lake kimberlitic rocks are not kimberlite but similar to the Sweet Grass minette, Montana alnöite or basanite. Mountain Lake samples with lower Mg# plot close to the Sweet Grass minette and basanite for Mg# versus SiO_2 and, in particular, close to the Sweet Grass minette for Mg# versus TiO_2.

Smith et al. (1985) further subdivided Group I kimberlites into Group IA (on craton) and Group IB (off craton) on the basis of their chemistry. Compared to Group IA, Group IB kimberlites have lower SiO_2 and higher CaO, FeO+Fe_2O_3 and volatile contents, as well as somewhat greater TiO_2, P_2O_5, Nb, Zr and Y. The TiO2 and K2O contents of the Alberta samples were plotted (Figure 8) and compared with the fields defined by Taylor et al. (1994). Except for six samples from the Birch Mountains (ABK53, ABK54, ABK56, ABK81, ABK82 and ABK83), the plot of TiO_2 versus K_2O places the Buffalo Head Hills and Birch Mountains samples into nonmicaceous Subgroup 1A and Subgroup 1B fields, respec-

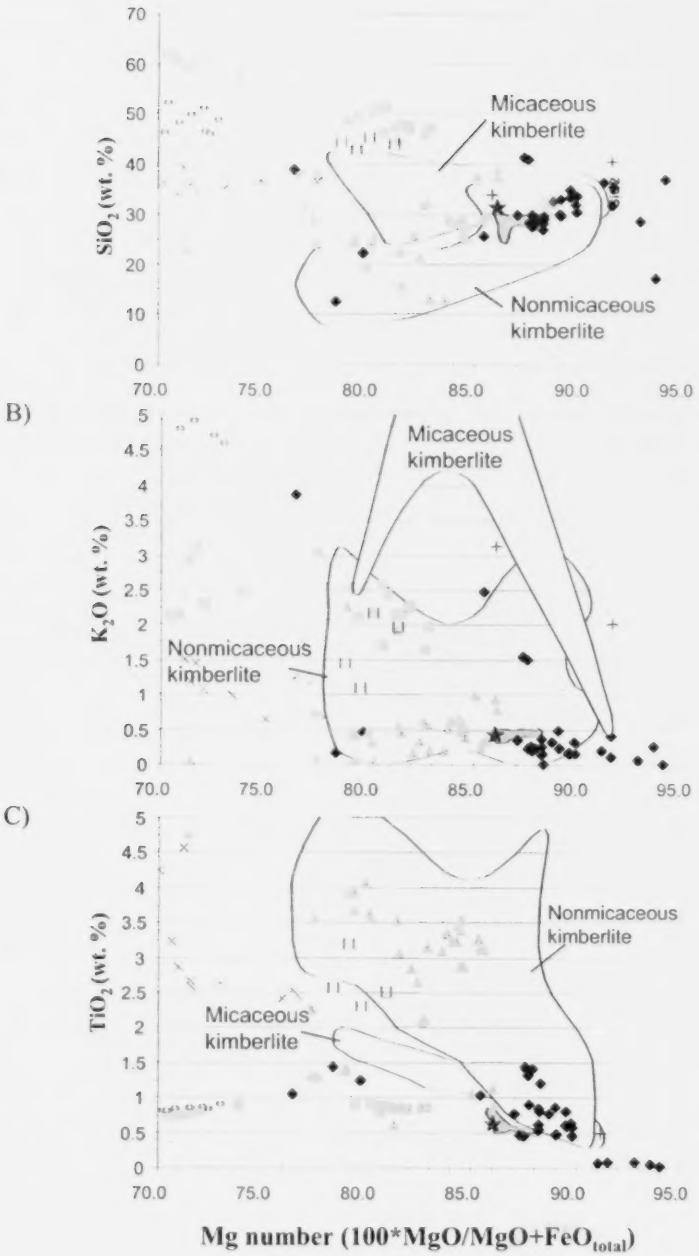

Figure 7. Plot of Mg# versus SiO_2, K_2O and TiO_2 for Alberta kimberlitic whole-rock compositions. Fields for South African Group I (nonmicaceous) and II (micaceous) kimberlites are from Clement (1982) and Smith et al. (1985). See section 2.4 in text for sources of comparative data.

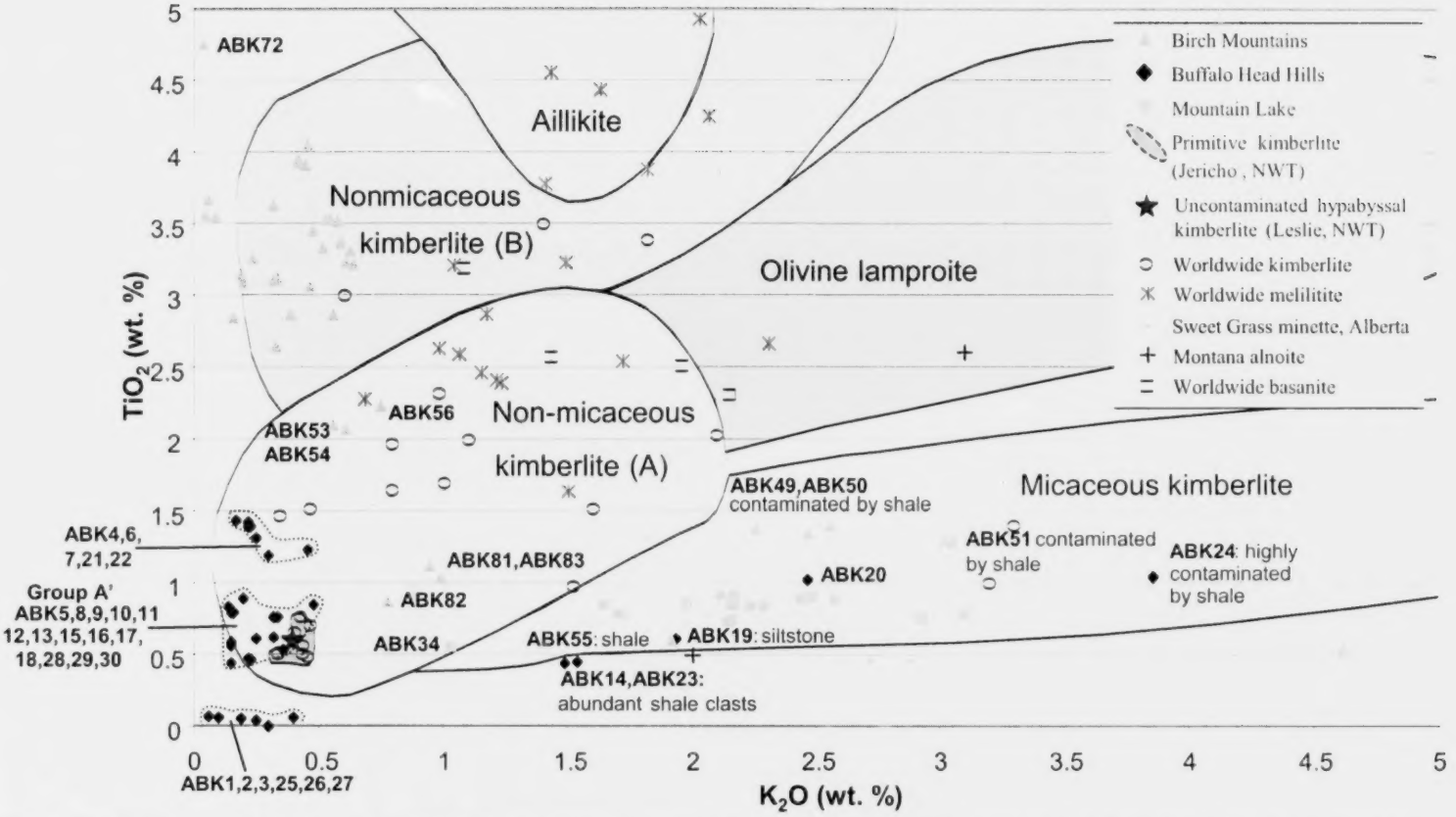

Figure 8. Plot of TiO_2 versus K_2O for Alberta kimberlitic whole-rock compositions. Fields for kimberlite and related rock types are from Taylor et al. (1994). See section 2.4 in text for sources of comparative data.

tively. Based on the criteria already discussed, the Buffalo Head Hills and Birch Mountains samples that plot in the Group II field are contaminated.

3.3 Compositional Variation Within Individual Pipes and Between Pipes in a Field

Important distinctions can be made between various pipes in a specific geochemical groupings. For example, samples ABK81, ABK82 and ABK83 (from the newly discovered Kendu pipe) and samples ABK53, ABK54 and ABK56 (from the Pegasus pipe) in the Birch Mountains plot in the Group IA field closer to the primitive kimberlite magma than samples from other pipes in the Birch Mountains (Figure 8). Hence, the Kendu pipe has a more primitive kimberlite geochemical signature that is much closer to the diamondiferous Buffalo Head Hills kimberlites than to other kimberlites in the Birch Mountains.

The contamination diagram (C.I. versus Ilm.I.) is used to compare compositional data where two or more samples were collected from an individual pipe (Figure 9). Samples from the Mountain Lake South pipe (ML95-3) have consistent compositions, whereas those from the Mountain Lake North pipe have a wide range of compositions, indicating that they have undergone more extensive crustal contamination. Sample material from the Mountain Lake South pipe represents the least contaminated sample material from the Mountain Lake pipes. Because the south pipe forms the major topographic high and the high-resolution aeromagnetic (HRAM) data show the two surface exposures join at depth to form a single root (Leckie et al., 1997), the high C.I. values from ML95-1 indicate that the north part of the pipe was subject to greater, but still variable, mixing with Wapiti Formation sedimentary rocks. Alternatively, the Mountain Lake North and South pipes may represent completely different magmatic events from the same conduit that are distinguished by slightly different chemistries.

The Buffalo Head Hills samples show good overall consistency between individual pipes. The high C.I. value for sample ABK19 (sampled at a depth of 52.0 m) is consistent with an epiclastic component in the upper portion of the pipe that is absent in deeper samples ABK20 to ABK22 (sample depth >79.5 m).

Multiple samples were taken from all eight Birch Mountain pipes. The data show relatively good correlation for the samples with low C.I. values (<2.0). Fourteen samples (ABK57 to ABK70) were collected from the Legend pipe at a sampling interval of approximately 20 m. The geochemistry of the Legend samples shows excellent consistency for the majority of the samples. Three Legend pipe samples (ABK63, ABK69 and ABK70) exhibit a slightly higher Ilm.I. The contamination of these samples is apparent in both hand specimens and thin section, and consists of weathered, incompetent or highly oxidized (sulphide) material.

4. Trace-Element Geochemistry

The trace-element geochemistry of kimberlites has been discussed by various authors (e.g., Dawson, 1962, 1967, 1980; Wedepohl and Muramatsu, 1979; Muramatsu, 1983; Smith et al., 1985; Mitchell, 1986, 1995; Taylor et al., 1994). In general, kimberlites are characterized by abundances of first-period transition-compatible elements (Sc, V, Cr, Ni, Co, Cu and Zn) similar to ultramafic rocks such as dunite and peridotite, and abundances of incompatible elements (e.g., Nb, Zr, Ta, Hf, U, Th, REE) similar to alkaline rocks such as melilitite, carbonatite, and potassic lavas.

Like the major elements, kimberlite trace-element geochemistry is subject to contamination problems. Incompatible trace-element abundances may be reduced by the presence of olivine macrocrysts and/or

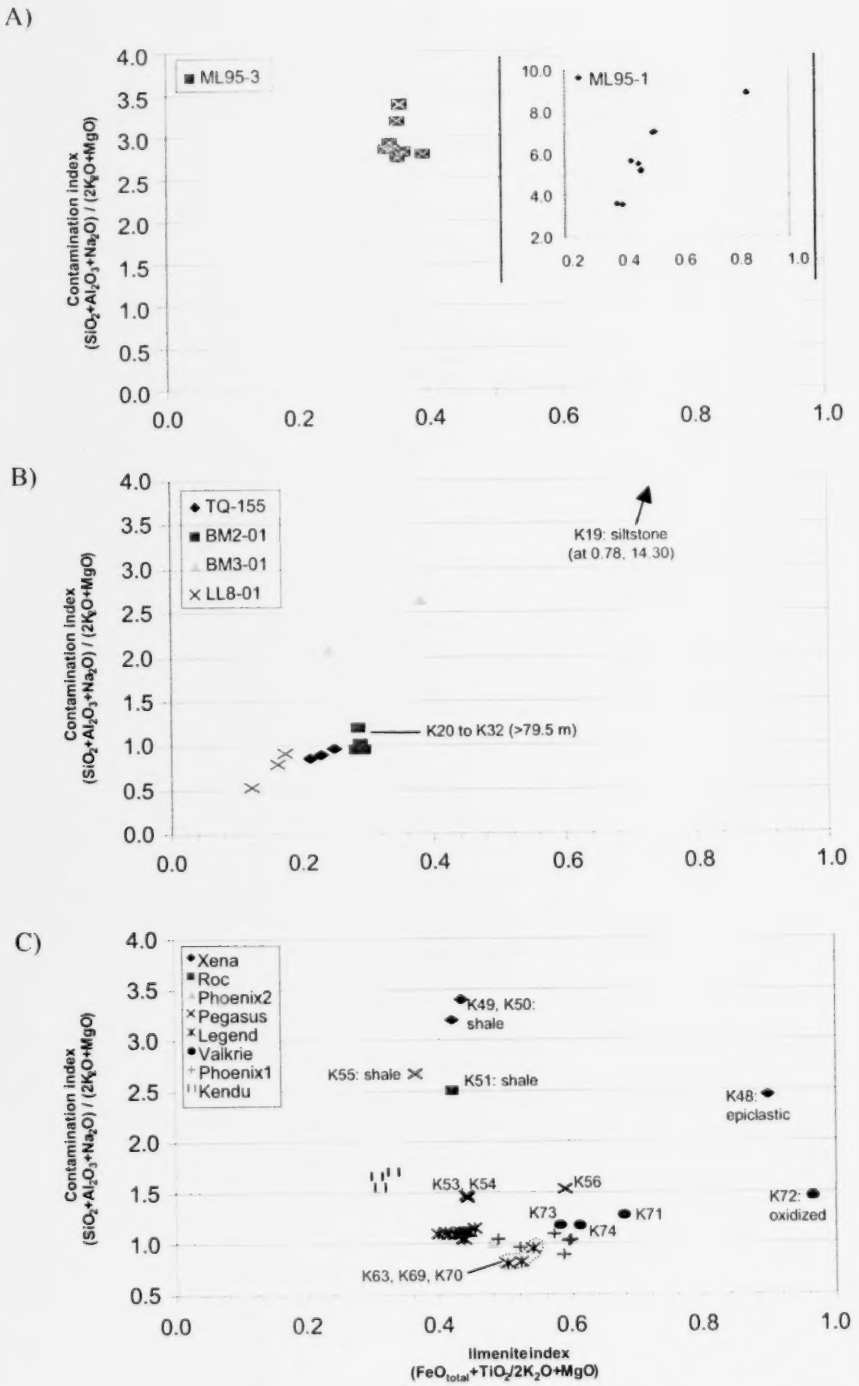

Figure 9. Whole-rock compositional variations in pipes with multiple samples A) Mountain Lake; B) Buffalo Head Hills; and C) Birch Mountains.

crustal contamination, but their interelement relationships remain unaffected and can be used to obtain information regarding the source regions of the magmas (Mitchell, 1986). Fesq et al. (1975) and Kable et al. (1975) concluded that elements such as Ti, Nb, Ta, Zr, Hf, and the rare earths are insignificantly affected by crustal contamination because of their high abundance in kimberlites and related rocks. Therefore, the trace elements are important criteria in the classification of kimberlite.

Because of the extremely high contents of Ni, Cr, Sr, Ba, REE, Zr and Nb in the Alberta samples relative to common crustal rocks, crustal contamination cannot be responsible for either the observed enrichment in these elements or the compositional variation within and between intrusions. Thus, the trace-element geochemistry supports the conclusion from major elements that whole-rock lithogeochemistry of pipes can be used as a tool for the classification of ultramafic rocks in northern Alberta.

4.1 Compatible-Element Variation Between Magmas

Duplicate analysis of ten randomly selected sample separates from drillcore found low relative error for the compatible trace elements (Table 1). The analytical reproducibility of the duplicate samples has an average relative error of less than 2.3% for the compatible elements, and ranges from 0.6% for Sc to 3.5% for Co.

Average values of Ni and Cr are lowest in samples from Mountain Lake (433 ppm Ni and 685 ppm Cr) and highest in samples from the Buffalo Head Hills (1241 ppm Ni and 937 ppm Cr). Concentrations of Ni and Cr in samples from the Mountain Lake pipes are well below those of worldwide kimberlite (Table 3) but comparable to the worldwide averages for melilitite (416 ppm Ni and 565 ppm Cr) and to the Sweet Grass minette (512 ppm Ni and 591 ppm Cr).

Concentrations of Ni and Cr from the Buffalo Head Hills and Cr from the Birch Mountains are similar to those of Group I South African kimberlites. Average Ni values in samples from the Birch Mountains (618 ppm) are slightly lower than Group IB Ni values (800 ppm). Price et al. (2000) noted that Cr and Ni concentrations were higher in their aphanitic samples and that high Ni concentrations (ranging from 600 to 1400 ppm) were associated with primitive mantle melts. Samples ABK8, ABK26 and ABK27 have the highest Ni values (1702, 2091 and 2171 ppm, respectively) of all Alberta samples. Cobalt shows a good correlation with Ni, and Co values are highest in samples ABK08 (115.5 ppm), ABK26 (102.5 ppm) and ABK27 (111.9 ppm).

The compatible elements from Alberta kimberlitic rock samples and various ultramafic rock types are plotted on a compatible-element distribution diagram (Figure 10), which has been normalized to the pyrolite abundance of Jagoutz et al. (1979). With the exception of Cu, the Mountain Lake, Buffalo Head Hills and Birch Mountains samples plot close to average kimberlite. Samples from the Buffalo Head Hills have the lowest concentrations of Sc, V, Cu and Zn, and the Birch Mountains samples have the highest values of Sc, V, and Cu. All samples are below compatible-element trends for tholeiitic basalt, alkali olivine basalt, Sweet Grass minette and melilitite.

4.2 Incompatible-Element Variation Between Magmas

Duplicate analysis of ten randomly selected sample separates from drillcore had a low relative error for the incompatible trace elements (Table 1). The analytical reproducibility of the duplicate samples has relative errors of <8.6% for alkaline earth elements and <5.7 % for the rare-earth elements. The analytical reproducibility of the alkali and volatile elements is <10% for Mo, Pb, As, Cd, Cs and Ga, and between 13.7% and 21.7% for Sb, Bi, C, S, Sn and W.

Table 3. Selected trace and major elements and element ratios from Alberta kimberlitic rocks and, for comparison, worldwide kimberlite, olivine melilitite and Sweet Grass minette.

Element	South Africa kimberlite[1]			Global kimberlite[2]		Average	Average	Average Sweet	Mountain Lake			Buffalo Head Hills			Birch Mountains		
or ratio	Group IA	Group IB	Group II	Group I	Group II	kimberlite[3]	melilitite[4]	Grass minette[5]	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Ni	1360.00	800.00	1400.00	NA**	NA	965.00	415.52	512.42	197.00	721.00	433.26	45.00	2171.00	1240.47	31.00	1165.00	618.36
Cr	1400.00	1000.00	1800.00	NA	NA	893.00	565.36	591.42	362.68	944.33	685.11	95.80	1512.30	937.26	123.17	1443.87	893.77
Co	83.00	79.00	85.00	NA	NA	65.00	NA	44.17	21.20	55.80	39.89	10.40	115.50	77.98	10.90	105.30	76.89
Cu	54.00	79.00	30.00	NA	NA	93.00	NA	70.00	29.00	49.00	42.65	3.00	63.00	28.17	26.00	78.00	54.03
Zn	56.00	75.00	60.00	NA	NA	69.00	NA	93.50	43.00	75.00	68.59	20.00	94.00	53.20	23.00	92.00	66.22
V	75.00	170.00	85.00	NA	NA	100.00	270.52	170.25	68.00	138.00	111.12	17.00	173.00	73.67	66.00	180.00	120.19
Sc	13.00	20.00	20.00	NA	NA	14.00	25.89	19.29	11.00	15.00	13.32	2.00	17.00	10.06	10.00	26.00	17.38
Nb	165.00	210.00	120.00	NA	NA	141.00	144.32	13.08	41.10	87.50	69.74	11.00	284.20	134.36	13.00	508.50	240.45
Zr	200.00	385.00	290.00	NA	NA	184.00	405.44	247.00	88.70	146.60	126.79	35.80	323.50	136.69	99.80	324.30	192.76
Y	13.00	30.00	16.00	NA	NA	22.00	26.48	17.17	13.50	21.70	16.16	0.70	21.60	9.95	9.00	22.30	14.92
Sr	825.00	1020.00	1140.00	NA	NA	851.00	1279.96	1316.75	319.00	544.30	421.65	123.50	1581.80	645.32	174.50	1408.70	743.32
Rb	50.00	30.00	135.00	NA	NA	73.00	48.15	167.83	41.50	104.80	74.79	1.10	135.90	25.38	3.70	195.40	39.91
Th	18.00	27.00	30.00	NA	NA	17.00	11.57	8.72	8.30	15.60	12.39	5.50	37.10	19.43	8.40	97.30	38.92
Ba	1000.00	850.00	3000.00	NA	NA	1100.00	919.13	2979.92	829.00	2641.00	1033.26	77.00	2704.00	971.91	471.00	3932.00	1287.31
La	90.00	125.00	200.00	NA	NA	150.00	98.89	42.04	44.10	80.70	64.72	13.10	320.70	127.19	43.00	487.60	204.48
Ce	140.00	220.00	350.00	NA	NA	200.00	191.48	89.68	81.70	147.10	117.99	25.20	596.20	237.94	84.00	882.50	363.19
Nd	90.00	100.00	145.00	NA	NA	85.00	83.75	42.92	31.60	52.90	42.80	6.90	197.90	76.45	34.90	281.90	118.04
Ga	4.00	8.00	6.00	NA	NA	5.70	NA	11.00	7.80	15.50	12.40	0.80	15.10	4.39	5.80	15.70	8.08
U	4.00	6.00	5.00	NA	NA	3.10	3.87	2.56	2.30	3.80	3.29	1.30	7.60	4.13	2.00	10.30	5.89
Pb	7.00	10.00	30.00	NA	NA	15.30	10.46	22.78	7.00	11.00	9.71	3.00	17.00	8.61	7.00	23.00	11.28
Hf	NA	NA	NA	NA	NA	5.60	12.81	6.16	2.80	3.80	3.34	0.80	7.80	3.40	2.50	9.10	5.17
P_2O_5/Ce*	78.57	50.00	31.40	58.00	33.00	NA	59.52	115.18	22.08	43.91	24.79	5.60	47.62	21.25	7.93	23.39	15.55
Nb/Zr	0.83	0.55	0.41	1.10	0.48	0.77	0.44	0.06	0.31	0.77	0.56	0.14	1.79	1.14	0.75	1.67	1.35
Nb/U	41.25	35.00	24.00	42.00	25.00	45.48	43.99	5.21	13.20	28.13	21.24	17.77	57.15	34.69	31.64	57.43	43.78
Nb/La	1.83	1.68	0.60	1.80	0.70	0.93	1.50	0.32	0.72	1.19	1.06	0.89	1.83	1.16	0.94	1.68	1.25
Nb/Ta	NA	NA	NA	NA	NA	12.80	12.63	20.26	14.67	16.67	15.94	10.60	20.13	14.31	10.52	37.02	15.82
TiO_2/Nb*	121.21	142.86	83.30	NA	NA	NA	290.45	753.92	97.48	177.62	123.90	4.33	89.89	42.26	75.88	145.28	116.62
La/Yb	NA	NA	NA	NA	NA	125.00	54.13	32.01	28.85	61.49	44.97	13.24	311.36	213.99	22.05	435.36	212.54
Ce/Sr	0.17	0.22	0.31	0.24	0.32	0.24	0.16	0.07	0.23	0.31	0.28	0.11	2.85	0.49	0.24	0.95	0.52
Ce/Y	10.77	7.33	21.88	NA	NA	9.09	7.20	5.25	4.62	10.11	7.45	17.95	40.23	29.21	15.68	43.47	26.71
Ba/Rb	20.00	28.33	22.22	26.00	19.00	15.07	21.07	17.92	9.52	36.23	14.69	8.83	727.27	88.83	15.95	339.55	63.31
Sc/Al_2O_3	5.00	6.45	6.25	7.20	6.00	NA	3.00	1.88	1.08	1.74	1.45	2.82	11.76	5.64	2.15	7.56	5.54
U/Th	0.22	0.22	0.17	0.21	0.17	0.18	0.41	0.30	0.22	0.33	0.27	0.11	0.32	0.20	0.09	0.23	0.15
Zr/Hf	NA	NA	NA	NA	NA	32.86	42.49	40.34	34.08	41.78	38.09	31.49	54.88	41.10	33.52	41.49	37.19
Ni/MgO	47.72	33.61	47.14	40.00	49.00	NA	27.10	50.06	27.49	96.33	39.87	22.15	53.24	40.25	20.04	48.74	28.58

[1] Smith et al. (1985) [2] Taylor et al. (1994) [3] Mitchell (1986); Muramatsu (1983)
[4] Rogers et al. (1992); Wilson et al. (1995) [5] Kjarsgaard (1994); Buhlmann et al. (2000) * Ratio x 104 NA = not available

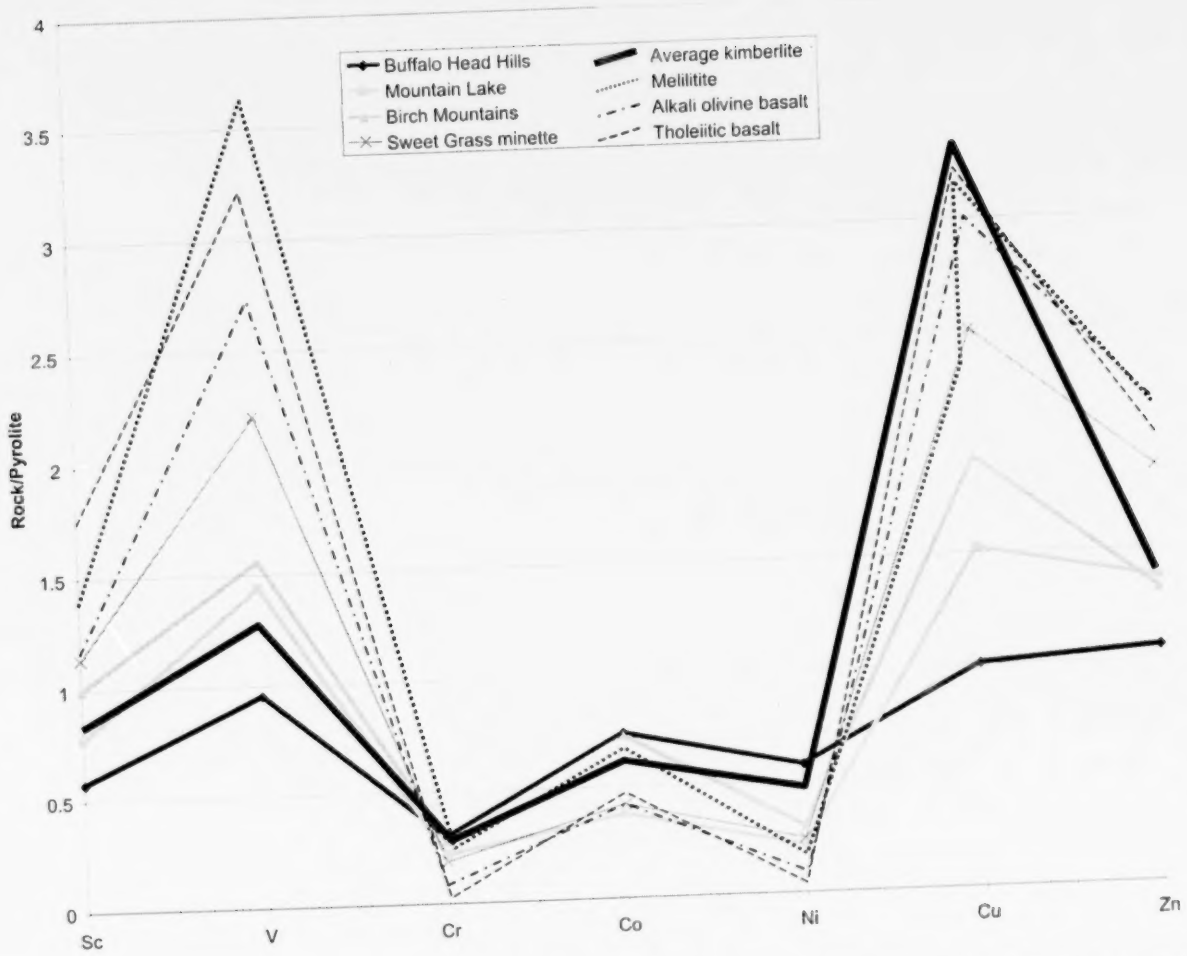

Figure 10. Compatible-element distribution diagram for Alberta kimberlitic whole-rock compositions. Average kimberlite, melilitite, alkali olivine basalt and tholeiitic basalt compiled from Mitchell (1986) are shown for comparison. Pyrolite abundance from Jagoutz et al. (1979).

The incompatible elements are presented in scatter-plot matrices (Appendices 4A, 4B, and 4C), in table form (Table 3), and as trace-element distribution diagrams (Figures 11, 13 and 14) and rare-earth element diagrams (Figure 12). Data from worldwide kimberlite and melilitite, Alberta minette and Montana alnöite are included for comparative purposes.

In general, the incompatible-element patterns in the Alberta samples are similar to those of worldwide kimberlite, in the case of Buffalo Head Hills and Birch Mountains, and to potassic alkali rocks, in the case of Mountain Lake. The scatter-plot matrices (Appendices 4A, 4B, and 4C) are used to recognize general correlations; moderate to good positive correlations exist for

- Rb, Ga, SiO_2, K_2O, Al_2O_3 and Na_2O_3;
- Sc, Zr, Y, Nb, La, Ce, Th, TiO_2, Fe_2O_3, MnO and P_2O_5;
- Pb, Ba and V; and
- MgO, Ni, Cr and Co.

The following sections describe major differences between the kimberlitic fields/clusters and comparisons with worldwide ultramafic rock types.

4.2.1 Mountain Lake

Compared to the Buffalo Head Hills and Birch Mountains areas, Mountain Lake is characterized by low Nb (70 ppm), LREE (e.g., Ce 118 ppm), Sr (422 ppm) and high Ga (12.4 ppm), Rb (75 ppm), and heavy rare-earth elements (HREE; La/Yb ratio of 45).

In contrast to the major elements and compatible trace elements, the incompatible-element distribution diagram (Figure 11A) shows that Mountain Lake is similar to kimberlite, but with lower trace-element abundances. Negative Rb, K, Sr, P and (slight) Ti anomalies and positive U, Ta-Nb, Nd and Sm anomalies characterize the distribution pattern. Although the major-oxide data showed some trends similar to the Sweet Grass minette and to basanite, the trace-element data highlight significant differences (Figure 11B). For example, Mountain Lake contains lower average values, than the Sweet Grass minette, of Sr (422 vs. 1317 ppm), Zr (127 vs. 247), Rb (75 vs. 168 ppm), V (111 vs. 170), Ba (1033 vs. 2980 ppm), and higher average values of Th (12 vs. 9 ppm) and Nb (70 vs. 13 ppm). Figure 11 also illustrates the difference between Mountain Lake and both the Roman Province–type (RPT) lavas and the Montana alnöite. In particular, the Ba and Nb anomalies are reversed. The positive Ta-Nb anomaly may be the single most obvious difference between Mountain Lake and minette, RPT and alnöite rocks, which are typically characterized by low Nb values. Niobium is hosted mainly by perovskite; Skupinsky and Langenberg (in press) have reported that fine-grained chromite, perovskite, ilmenite and magnetite are randomly distributed in the matrix, and that perovskite occurs ubiquitously in destroyed olivine rims.

To see if Wapiti Formation sedimentary rocks influence the incompatible-element distribution of the Mountain Lake samples, we plotted (Figure 11B) the average trace-element values from four Wapiti Formation samples, which were collected adjacent to the pipes by Dufresne et al. (2001). The incompatible-element profiles of the sedimentary rocks do not resemble those of the Mountain Lake pipes. The Wapiti Formation samples have a negative Th and Ta anomaly, which is similar to the RPT lavas, the Montana alnöite and the Sweet Grass minette. A low, negative P anomaly and positive Hf, Zr and Sm anomalies, however, distinguish the Wapiti sedimentary rocks from all rock types plotted on Figure 11B.

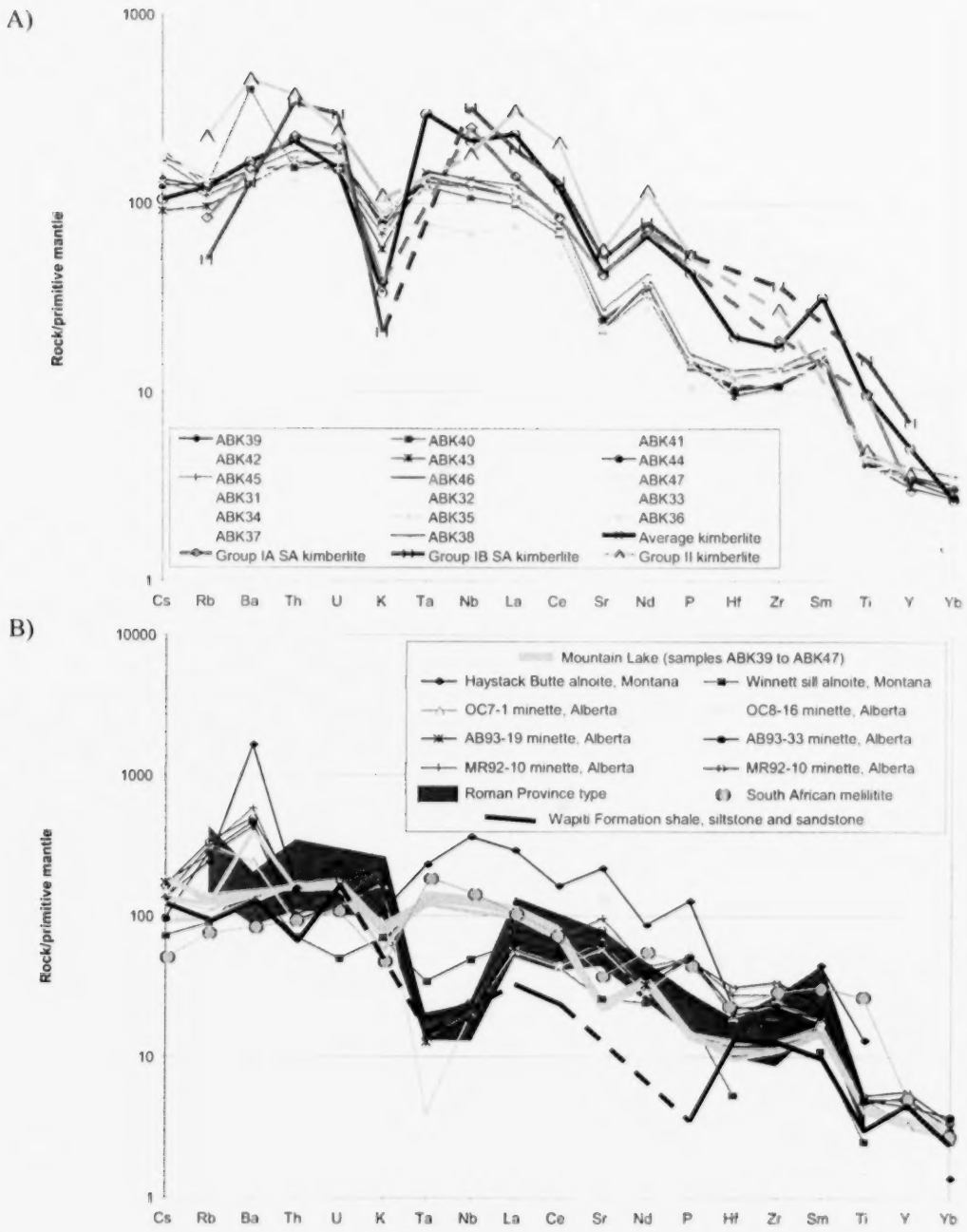

Figure 11. Incompatible-element distribution diagram for whole-rock compositions from the Mountain Lake pipes. Average kimberlite (Mitchell, 1986; Muramatsu, 1983), Group I and Group II kimberlite (Smith et al., 1985), Montana alnöite (Hearn, 1986), Sweet Grass minette (Buhlmann et al., 2000), Roman Province–type lavas from Mount Ernici and Mount Vulsini (from Mitchell, 1995; after Peccerillo et al., 1988), South African melilitite (Rogers et al., 1992) and Wapiti Formation sedimentary rocks (Dufresne et al., 2001) are shown for comparison. Primitive mantle values from McDonough and Sun (1995).

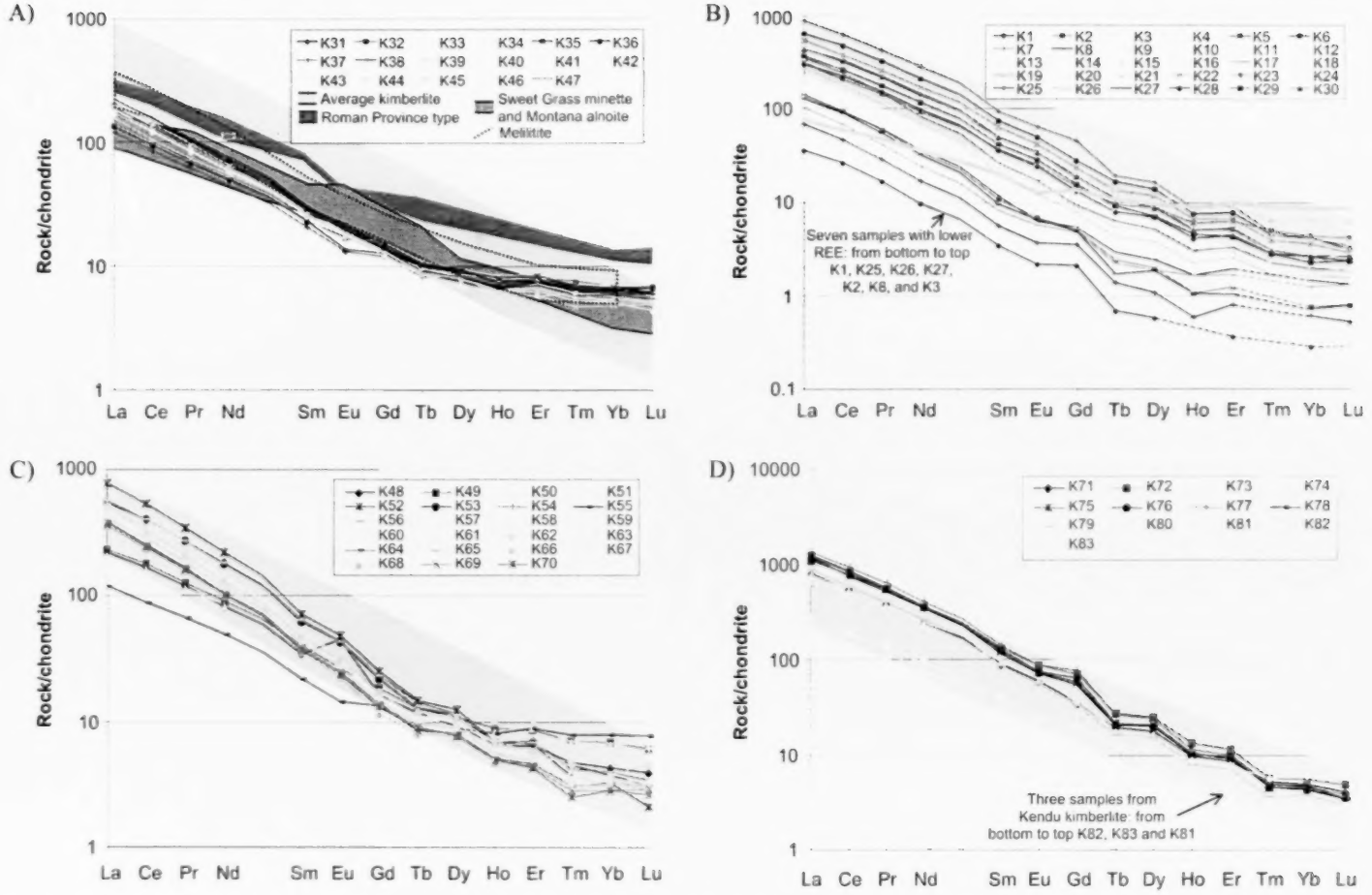

Figure 12. Chondrite-normalized rare-earth element patterns for Alberta kimberlitic whole-rock compositions: A) Mountain Lake; B) Buffalo Head Hills; and C) and D) Birch Mountains. Note that sample numbers are shortened (i.e., K31=ABK31). Shaded pattern represents average worldwide kimberlite (Mitchell 1986). Rare-earth element patterns in B): Roman Province–type lavas from Ernici, Italy (Civetta et al., 1981); olivine minette from Sweet Grass Hills, Alberta (Kjarsgaard, 1994; Buhlmann et al., 2000); and alnöite from Montana (Hearn, 1986). Chondrite values form Taylor and McLennan (1985).

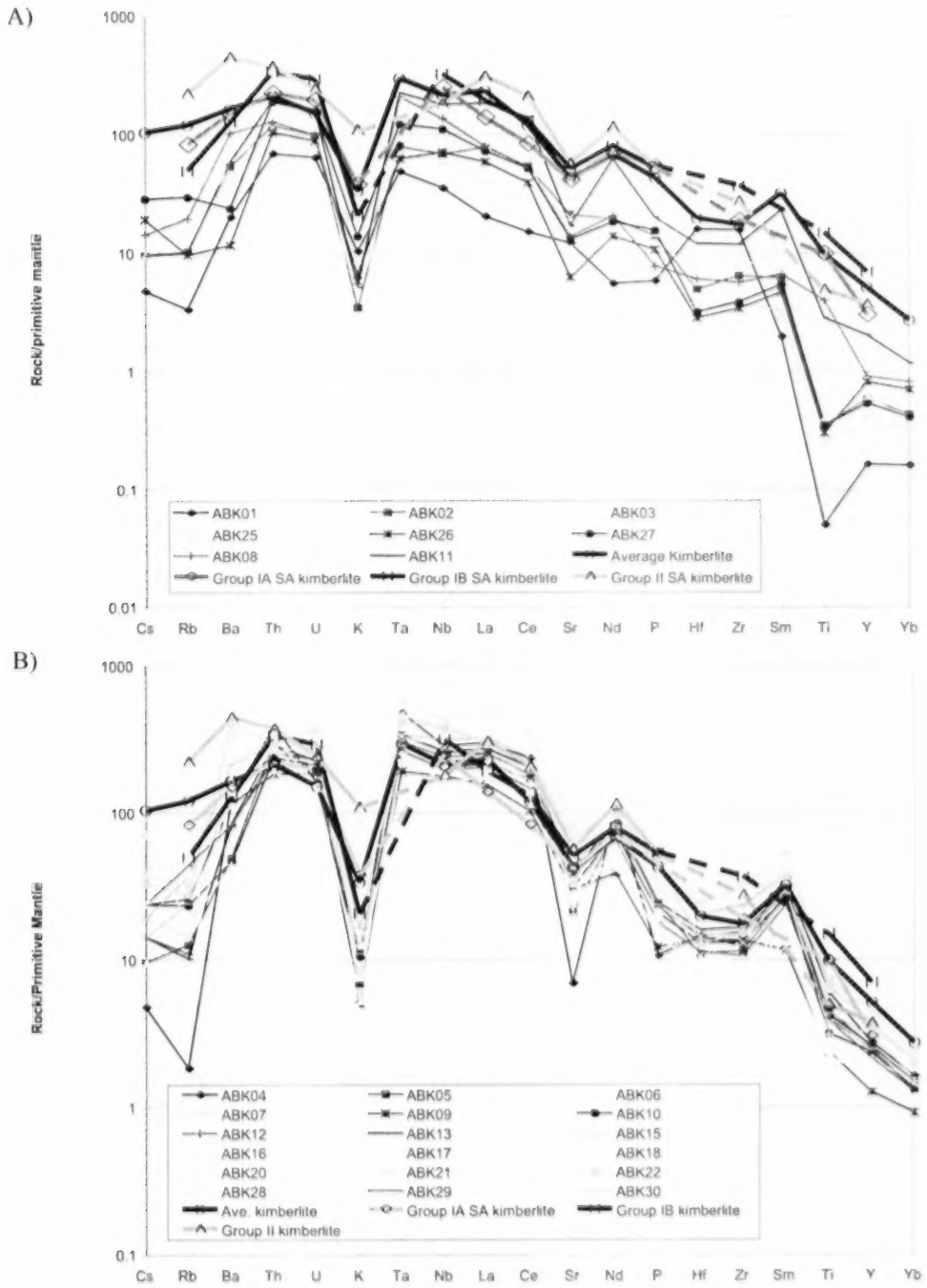

Figure 13. Incompatible-element distribution diagram for whole-rock compositions from the Buffalo Head Hills. Average kimberlite (Mitchell, 1986; Muramatsu, 1983) and Group I and Group II kimberlite (Smith et al., 1985) are shown for comparison. Primitive mantle values from McDonough and Sun (1995).

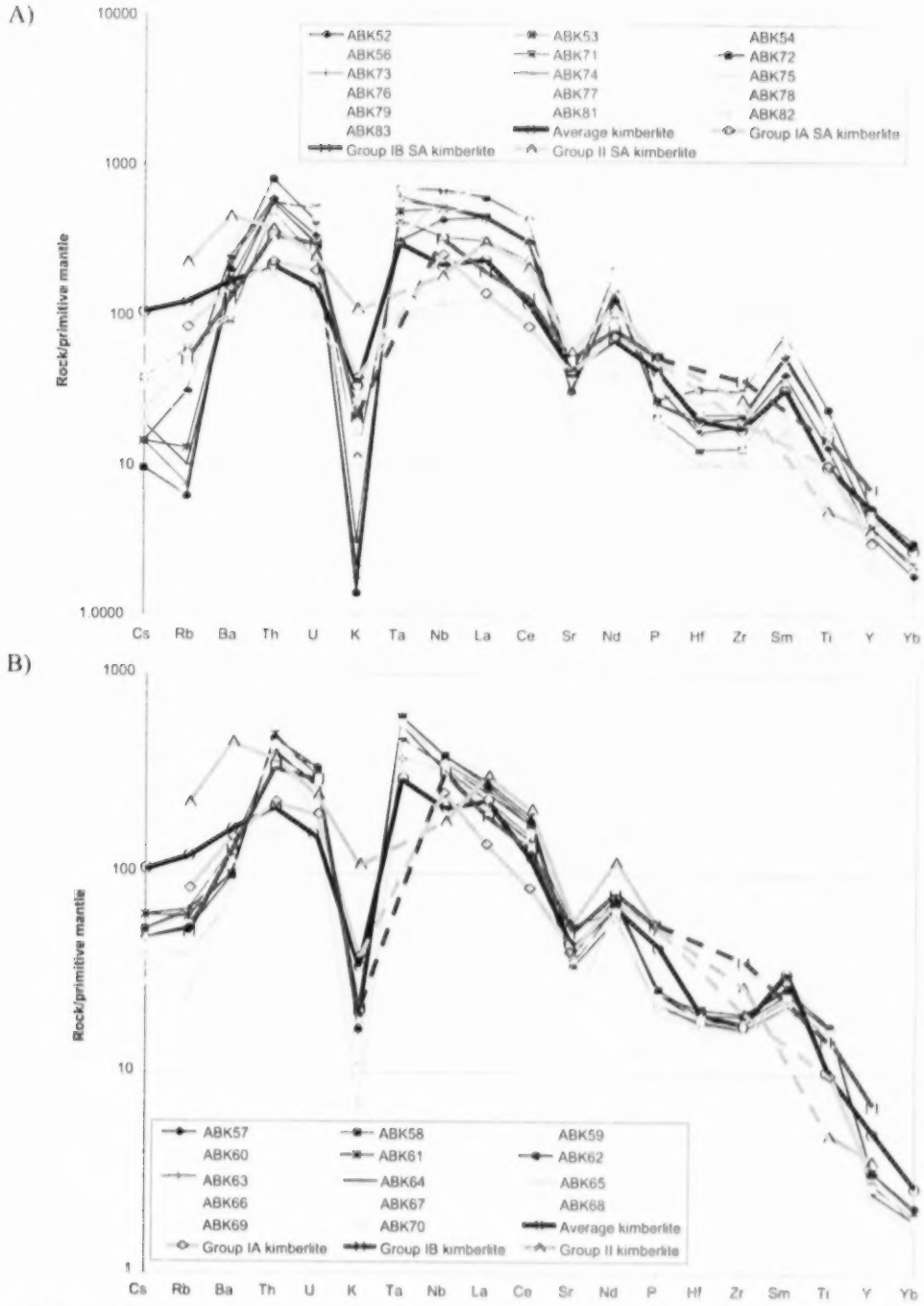

Figure 14. Incompatible-element distribution diagram for whole-rock compositions from the Birch Mountains. Average kimberlite (Mitchell, 1986; Muramatsu, 1983) and Group I and Group II kimberlite (Smith et al., 1985) are shown for comparison. Primitive mantle values from McDonough and Sun (1995).

In contrast to the major-element data, the closest trace-element distribution pattern is that of the melilitite (Figure 11B), in which the distribution pattern has higher Nb and LREE combined with conspicuous negative anomalies or relative depletions for K and P.

The REE abundances from the Mountain Lake pipes are the lowest of all the samples except the contaminated rocks from the Buffalo Head Hills and Birch Mountains. The sum of yttrium and the lanthanides (ΣY, La-Lu) from Mountain Lake is 273, compared with values of 496 for the Buffalo Head Hills and 770 for Birch Mountains. Mountain Lake exhibits a flatter chondrite-normalized REE profile relative to Buffalo Head Hills and Birch Mountains (Figure 12A). Light rare-earth element enrichment (90 to 210 times chondrite abundance for La) and the average La/Yb ratio (44) are lower than for average kimberlite (Table 3). Such a profile may reflect either crustal contamination of the Mountain Lake samples, a nonkimberlitic original REE pattern, or both.

The REE pattern from the Sweet Grass olivine minette, Montana alnöite and melilitite are included on Figure 12A for comparison. Total REEs from Mountain Lake are considerably lower than those of the RPT lavas and melilitite. Despite a slight concave down trough between Sm and Ho, the REE profile from the Mountain Lake pipes closely resembles those of the Sweet Grass olivine minette and the Montana alnöite.

Alibert et al. (1983) suggested that Ce/Yb ratios are distinctive for alkali basalt, melilitite and kimberlite, and measure 40 to 100 times chondrite for kimberlite, 20 to 30 times for melilitite; and 8 to 15 times for alkali basalt. The Buffalo Head Hills and Birch Mountains kimberlites exhibit average Ce/Yb ratios of 104 and 97 times chondrite, respectively. However, Mountain Lake has a very low Ce/Yb ratio, between 14 and 29, and averaging 21, times chondrite. Using the criteria of Alibert et al. (1983), the Mountain Lake is not kimberlite, but more likely an alkali basalt and melilitite.

4.2.2 Buffalo Head Hills

High Ni (up to 2171 ppm) and low V (average 74 ppm), Y (average 10 ppm), Pb (average 9 ppm), Sr (average 645 ppm) and Ga (average 4 ppm) characterize the Buffalo Head Hills samples, compared to those from Mountain Lake and Birch Mountains. The Cr content, which averages 937 ppm in the Buffalo Head Hills, is comparable with worldwide kimberlite and only slightly higher than that of the Birch Mountains (average 894 ppm Cr).

The incompatible-element distribution diagram (Figures 13A and B) for the Buffalo Head Hills is similar to that of Group I kimberlite. The relative depletions in K and P may suggest that minerals such as phlogopite and apatite were residual in the source during partial melting. The relative depletion in Sr may be due to either the presence of a residual Sr-bearing phase, such as phosphate, or to intrinsic depletion of the mantle in clinopyroxene, and hence Sr, by previous episodes of basaltic magma formation. Potassium richterite is another possible residual phase, which might retain Sr, Rb and K. Mitchell (1995) noted that a significant negative Sr anomaly, plus Rb and K depletion, suggest 'off-craton' kimberlite. It should be noted, however, that both South African Group IA and Group IB kimberlite (Smith et al., 1985) have a similar negative Sr anomaly.

Samples ABK01, ABK02, ABK03, ABK08, ABK11, ABK25, ABK26 and ABK27 are plotted on Figure 13A. These samples contain lower overall incompatible element abundance compared to the rest of the Buffalo Head Hills kimberlites (Figure 13B), particularly for Rb, LREE, Nd, Hf and Ti. Samples ABK01 and ABK25 are the only kimberlite samples that do not exhibit a negative Sr anomaly. Samples ABK06, ABK07, ABK21 and ABK22 have the highest abundance of incompatible elements in the Buffalo Head Hills.

The REE plots are normalized to chondrite (Figure 12B) and show two distinct groups with differing REE abundances but similar degrees of REE fractionation. Most of the Buffalo Head Hills samples plot within the shaded REE pattern for average kimberlite. Accordingly, they exhibit extreme LREE enrichment (300 to 870 times chondrite abundance for La) with La/Yb ratios of 214. Samples ABK06, ABK07 and ABK22 have the highest abundance of REE in the Buffalo Head Hills. A less REE-enriched group of samples (ABK1, ABK2, ABK3, ABK8, ABK25, ABK26 and ABK27) is characterized by lower LREE enrichment (35 to 145 times chondrite abundance for La) and slightly lower La/Yb ratios of 196. Because the C.I. and Ilm.I. of these samples are low (*see* Figure 2), the slightly higher HREEs and low REE abundance, relative to the rest of the Buffalo Head Hills samples, may be the result of alteration.

One sample (ABK19) is also located in this group, but its low La/Yb ratio (13) and high HREEs support the degree of contamination previously noted in this sample (*see* Figures 2 and 3).

4.2.3 Birch Mountains

Compared to the Buffalo Head Hills and average worldwide kimberlite, the Birch Mountains pipes are characterized by high concentrations of Nb (average 240 ppm and up to 509 ppm). The Birch Mountains pipes contain comparable amounts of Cr to the Buffalo Head Hills pipes, but appreciably lower values of Ni (average 618 ppm vs. average 1240 ppm). The Birch Mountains contain slightly to moderately higher average values of trace elements than the Buffalo Head Hills, including V (120 ppm), Sc (17.4 ppm), Zr (193 ppm), Hf (5.2 ppm), Y (14.9 ppm), Ba (1287 ppm), Rb (40 ppm), LREE (e.g., 204 ppm La), Ga (8.1 ppm) and Pb (11.3 ppm). The incompatible-element distribution diagram for the Birch Mountains exhibit high overall incompatible elements, with negative Rb, K, Sr and Hf anomalies and positive Ba-Th, Ta-Nb-La, Nd and Sm anomalies (Figures 14A and B) .

Incompatible-element distributions for samples from the Legend pipe (ABK57 to ABK70) are presented in Figure 14B and are similar to those of the other Birch Mountains samples except for the Ta-Nb-La anomaly. The Ta anomaly is more pronounced in the Legend pipe than in the rest of the Birch Mountains pipes (Figure 14A), which have a broad, flat Ta-Nb-La anomaly and a noticeably more negative K anomaly. Samples from the Kendu pipe (ABK81, ABK82 and ABK83) are characterized by their low overall incompatible element values. Samples from the Phoenix pipe (samples ABK75 to ABK79) exhibit the highest abundance of incompatible elements and the highest positive anomalies (Th, Ta to Ce, Nd and Sr).

The REE plots from the Birch Mountains are normalized to chondrite (Figure 12C and D). Most of the samples coincide with the REE pattern for average kimberlite. Generally, the majority of the Birch Mountains samples exhibit extreme LREE enrichment (390 to 1400 times chondrite abundance for La) with La/Yb ratios of 213. Samples with lower LREE enrichment and higher HREE enrichment are attributed to sample contamination. For example, samples ABK49, ABK50, ABK55 and ABK80 have a La/Yb ratio of between 22 and 50. These samples correspond to highly contaminated kimberlite (see Figures 2 and 3). Samples from the Kendu kimberlite (ABK81, ABK82 and ABK83) are less contaminated and exhibit a lower LREE enrichment and La/Yb ratio (135). The Birch Mountain REEs form a positive trend with Nb (Figure 15). This diagram reinforces the presence of a degree of REE and incompatible-element enrichment in the Birch Mountains consistent with the more evolved nature of these samples.

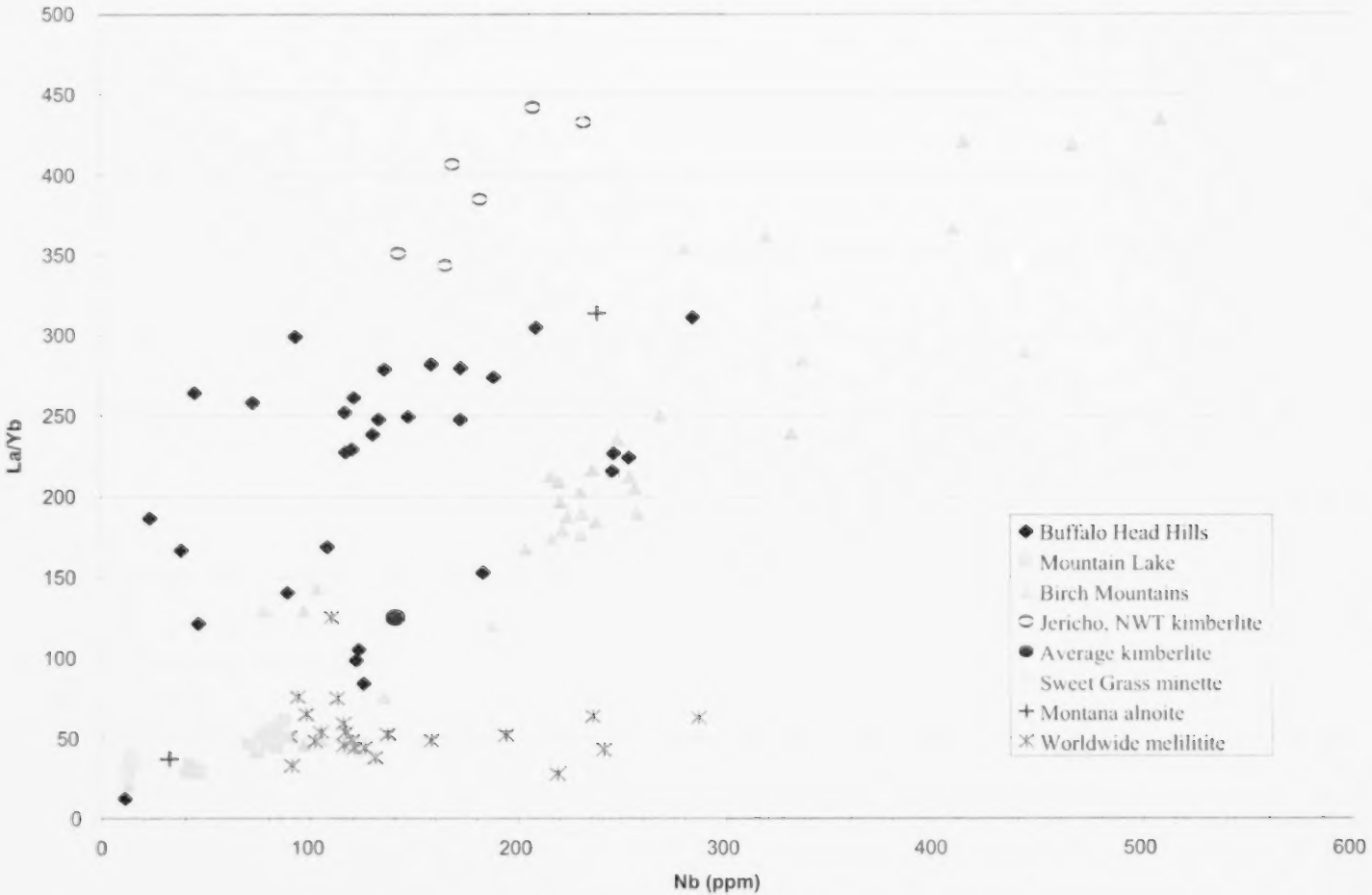

Figure 15. Plot of rare-earth elements versus Nb for Alberta kimberlitic whole-rock compositions. See section 2.4 in text for sources of comparative data.

5. Discussion

5.1 Linear Relationships Using Principal-Component Analysis

Principal component analysis (PCA) was carried out using whole-rock geochemical data from the Mountain Lake, Buffalo Head Hills and Birch Mountains samples. In addition, data were included from the Jericho kimberlite, NWT (Price et al., 2000) and Group IA, IB and II South African kimberlites (Smith et al., 1985). The analysis was completed using the S-PLUS program of Grunsky (2001). The program allows for the computation and same-figure plotting of principal component factor loadings for solutions of the scores of both the variables (R-mode) and the samples (Q-mode). Different combinations of the Alberta ultramafic rock dataset were recalculated with PCA to investigate the issue of closure (skewed by dominant components). For example, when PCA was done using only trace elements, no significant differences were observed in the component 1 versus component 2 results. That is, the results still show two distinct trends: one for the Buffalo Head Hills and Birch Mountains kimberlites and one for the Mountain Lake alkali ultramafic rocks and contaminated kimberlite. However, the issue of closure remains a possibility and more testing is required.

For this study, the objective of the PCA was to evaluate multivariate Alberta kimberlitic data for any linear relationships. We present and discuss the results of PCA for components 1 and 2 using a select number of variables, including the major elements SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, K_2O, Na_2O, MnO, TiO_2, P_2O_5 and Cr_2O_3, and the trace elements Ba, Ni, Ga, Nb, Rb, Sr, Th, V, Zr, Y and Pb. Components 1 and 2 account for 90.7% of the variance in 83 samples. Components 1, 2, 3, 4 and 5 account for 71.2%, 19.5%, 9.1%, 1.0% and 0.1% of the total variance, respectively. The relative contributions of selected major and trace elements to principal components 1 to 5 are presented on Table 4 and discussed below.

The R and Q mode scores of component 1 versus component 2 (Figure 16) illustrate two distinct trends.

5.1.1 Kimberlite Trend

The left side of Figure 16 shows a trend of samples associated with kimberlites from the Buffalo Head Hills and Birch Mountains. We interpret this trend to represent a magma evolution line from primitive to evolved kimberlite. A low component 2 score (negative load) is related to high MgO, Ni and Cr_2O_3, or primitive kimberlite ('P' in Figure 16). This end of the line supports previous conclusions that samples from the Buffalo Head Hills represent the most primitive kimberlite magma in the current data set. The high component 2 score (positive load) is related to high TiO_2, P_2O_5, MnO, Fe_2O_3, Nb, Th and Zr. This end of the mixing line is interpreted to represent the most evolved kimberlite in the current data set ('E' in Figure 16). The high component 2 loadings (i.e., high TiO_2, Nb, etc.) are characteristic of the Birch Mountains. The Phoenix kimberlite (samples ABK75, ABK76, ABK77 and ABK78), which was earlier interpreted as having the highest abundance of incompatible elements, plots as the most evolved kimberlite in the current data set.

Primitive kimberlite from the Jericho kimberlite in the Northwest Territories plots closer to the primitive end of the kimberlite trend. The average values for Group IA South African kimberlite plot in the middle of the trend. The average values for Group IB South African kimberlite plot close to those of the Phoenix pipe, closer to the evolved end of the trend.

5.1.2 Mountain Lake Trend

The component 1 association of SiO_2, Na_2O, AL_2O_3, K_2O, Rb and Ga characterizes samples that either

Table 4. Relative contributions of selected major and trace elements to principal components 1 to 5: A) R- scores with positive values in bold; and B) relative contribution expressed as percentages with values greater than 35% in bold.

A)

	Component				
	1	2	3	4	5
SiO_2	***0.8820***	-0.1613	***0.2041***	-0.2506	***0.0625***
Al_2O_3	***0.9292***	***0.2666***	***0.1342***	-0.0265	-0.0359
Fe_2O_3	-0.6806	***0.4963***	***0.3472***	-0.2388	-0.1406
MgO	-0.7598	-0.4949	***0.0618***	-0.3273	***0.0279***
CaO	-0.3518	***0.5222***	-0.4982	***0.5147***	-0.1925
Na_2O	***0.8814***	***0.1225***	***0.0320***	-0.0846	-0.0883
K_2O	***0.9008***	***0.2308***	-0.1556	-0.1473	-0.0866
TiO_2	-0.4822	***0.6805***	***0.4425***	***0.1138***	-0.0712
P_2O_5	-0.4563	***0.6874***	-0.3679	-0.1571	-0.0281
MnO	-0.5693	***0.6065***	-0.0072	***0.1062***	-0.3854
Cr_2O_3	-0.7804	-0.0848	***0.1067***	-0.3196	-0.2091
Ba	***0.1109***	***0.6855***	-0.4345	-0.3890	-0.1043
Ni	-0.5678	-0.6594	-0.1936	-0.2893	-0.0382
Ga	***0.7959***	***0.4739***	***0.3027***	-0.0271	-0.0451
Nb	-0.6883	***0.6628***	***0.1969***	-0.0505	***0.0738***
Rb	***0.8624***	***0.3065***	-0.1492	-0.1622	-0.0616
Sr	-0.3636	***0.6142***	-0.4629	-0.0487	***0.3345***
Th	-0.5868	***0.6507***	***0.2551***	-0.1419	***0.1234***
V	***0.3290***	***0.7139***	***0.2004***	***0.0426***	-0.1494
Zr	-0.2265	***0.7925***	***0.1796***	***0.0978***	***0.4011***
Y	***0.3866***	***0.8279***	***0.0915***	***0.0550***	***0.0306***
Pb	***0.3142***	***0.7602***	-0.2476	-0.2914	***0.0445***

B)

	Component				
	1	2	3	4	5
SiO_2	***79.1179***	2.3174	4.2102	6.4208	0.7315
Al_2O_3	***87.1912***	7.7323	1.6873	0.0941	0.0525
Fe_2O_3	***47.1832***	24.9005	12.1307	6.0205	1.9897
MgO	***57.8113***	25.2250	0.5029	10.9472	0.0163
CaO	12.7799	27.3350	26.6048	24.7460	3.8013
Na_2O	***78.5737***	1.7271	0.0747	0.7266	0.1004
K_2O	***81.7254***	5.6741	2.4534	2.2037	0.5528
TiO_2	23.9976	***46.5137***	19.5685	1.5216	0.7914
P_2O_5	21.5830	***47.2931***	13.8469	2.7259	0.0314
MnO	33.2325	***36.9876***	0.0212	0.8799	13.6147
Cr_2O_3	***61.4032***	0.7854	1.1822	10.7245	2.9109
Ba	1.1000	***47.1809***	18.8076	14.8462	0.2032
Ni	31.8677	***43.9147***	3.7285	9.7642	0.1178
Ga	***63.0389***	24.0196	8.8260	0.1074	0.2527
Nb	***48.6357***	***43.8179***	3.8953	0.1812	0.7833
Rb	***74.8006***	9.8797	2.2340	2.6670	0.4253
Sr	13.8104	***37.4814***	21.6299	0.2046	11.3245
Th	***35.4716***	***42.1817***	6.7531	1.6108	2.2413
V	10.6659	***52.3563***	3.8097	0.1324	4.3217
Zr	5.5192	***62.8429***	3.2295	1.4479	17.3736
Y	14.7223	***70.3521***	0.6869	0.2595	0.2900
Pb	8.3191	***60.0027***	4.4590	10.0140	0.1655

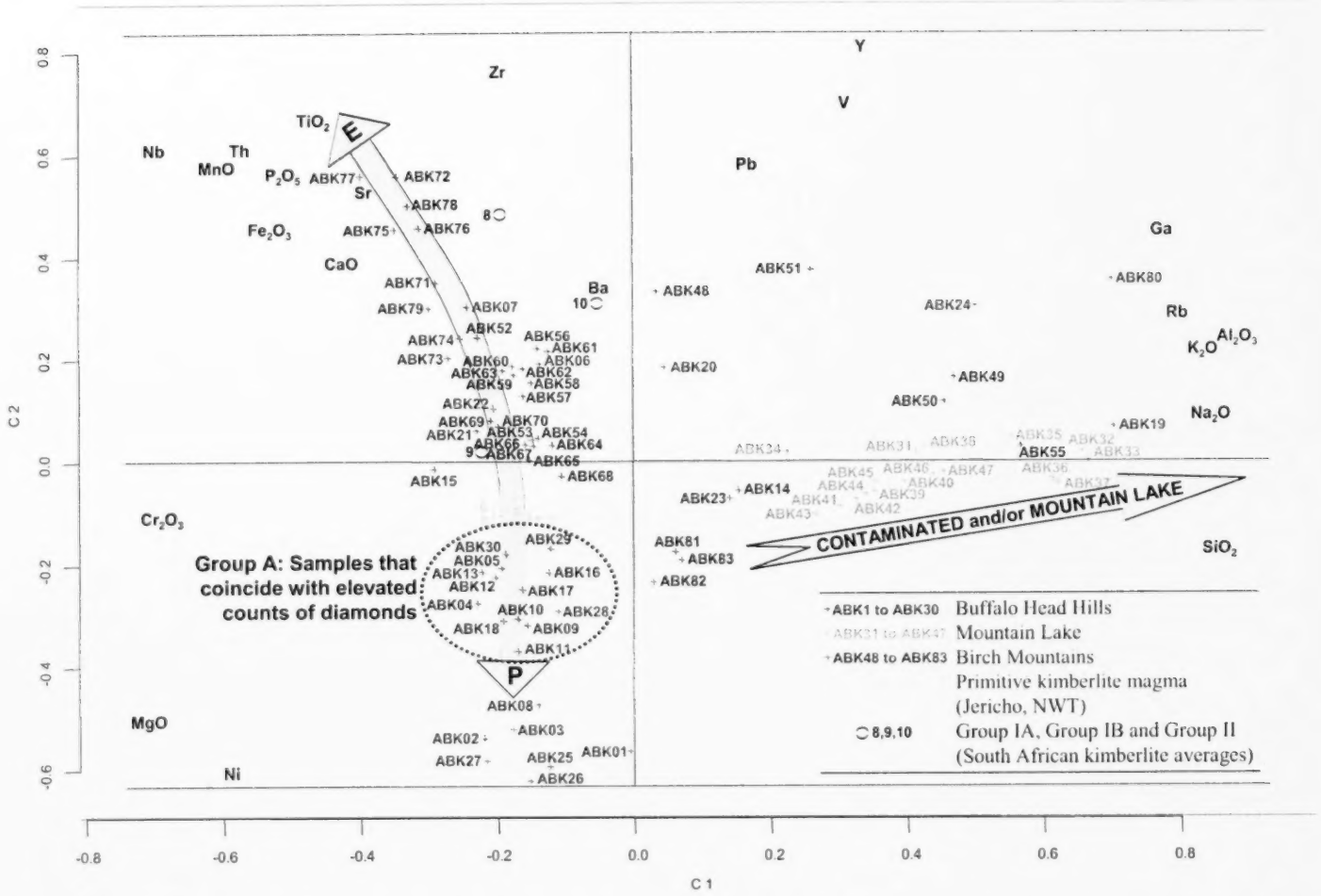

Figure 16. Principal-component analysis of selected major and trace elements from Alberta kimberlitic whole-rock compositions. Arrows indicate line fo descent directions for primitive (P) to evolved (E) kimberlite, and the direction for kimberlite contamination and/or Mountain Lake hybrid-type rocks. Kimberlite values from Jericho, Northwest Territories (Price et al., 2000) and South Africa (Smith et al., 1985).

have undergone crustal contamination or, more commonly, are associated with potassic alkali rocks associated with the Mountain Lake. Medium component 1 scores characterize Mountain Lake trend. As was the case for most of the bivariate plots, samples from Mountain Lake are divided into two groups on Figure 16. Samples from drillhole ML95-1 (samples ABK31 to ABK38) have been characterized as the more contaminated rocks. These plot close to ABK19 from the Buffalo Head Hills, which is highly contaminated by siltstone and shale. Samples from drillhole ML95-3 (samples ABK39 to ABK48) are interpreted to represent either the least contaminated, or the most primitive, magma associated with the Mountain Lake pipes. Accordingly, they plot toward the low component 1 score, characterized by high MgO, Ni and Cr_2O_3. Contaminated samples, including ABK49, ABK50, ABK55 and ABK80 from the Birch Mountains and ABK19 and ABK24 from the Buffalo Head Hills, are somewhat incorporated into the Mountain Lake trend, as component 2 consists of high loads from SiO_2, Na_2O, K_2O, Al_2O_3, Rb and Ga.

The PCA supports the interpretation presented in Sections 3 and 4. For example, a similar trend from primitive to evolved kimberlite and a higher SiO_2 trend for Mountain Lake and contaminated samples are evident on Figure 8.

5.2 Geochemistry and Diamond Content

Several authors have tried to relate bulk kimberlite chemistry to diamond potential. For example, Ilupin et al. (1974) suggested that average Rb content of diamondiferous kimberlites (23 ppm) from Yakutia, USSR is less than that of barren kimberlites (64 ppm). Akimov and Semenov (1970), Lutts and Mineyeva (1973) and Marshintsev and Lapin (1976) demonstrated that diamondiferous kimberlites from the Siberian platform have lower U (1.2 ppm) and Th (6.7 ppm) contents than barren kimberlite (2.5 ppm U and 17.5 ppm Th). Mitchell (1986) noted that these hypotheses are not supported by data for South African kimberlites. The Alberta pipes do contain lower concentrations Rb, U and Th for primitive samples, but these do not necessarily relate to diamond content.

Pipes in northern Alberta that include known elevated concentrations of diamonds are restricted to the Buffalo Head Hills. To date, Ashton has 'mini-bulk' sampled six kimberlite pipes on the basis of elevated micro- and macrodiamond contents discovered by Ashton during preliminary evaluation of samples from drillcore and trenches (Ashton Mining of Canada Inc., 1998, 1999a, 2000b). These pipes include kimberlites K5 (sample ABK04, this study), K6 (samples ABK05 and ABK29), K11 (samples ABK08 and ABK09), K14 (samples ABK10 to ABK13 and ABK30), K91 (sample ABK15) and K252 (not included in this study). These pipes are located on either the southeastern flank of the Buffalo Head Hills (kimberlites K5, K6, K14, K91 and K252) or in the centre of the Loon River lowlands (kimberlite 11). For the purpose of comparing diamond content with whole-rock geochemistry, we have selected the same pipes that Ashton mini-bulk sampled as being representative of kimberlite with 'elevated' diamond content.

Principal component analysis of the data shows that most of the Buffalo Head Hills pipes with elevated diamond contents have similar geochemistry, with samples ABK04, ABK05, ABK09, ABK10, ABK11, ABK12, ABK13, ABK16, ABK17, ABK18, ABK28, ABK29 and ABK30 forming a tight grouping near the primitive magma endpoint (labelled Group A on Figure 16). For a comparison with previous work presented in this paper, the majority of the Group A samples from Figure 16 also form a cluster (Group A') on the plot of TiO_2 versus K_2O (Figure 8).

There are also, however, samples from pipes with elevated diamond content that exhibit different geochemistry. These include kimberlite K91 (sample ABK15) and kimberlite K11 (sample ABK8), which were bulk sampled but do not plot in Group A on Figure 16, and kimberlite TQ155 (samples ABK16,

ABK17 and ABK18), which was not bulk sampled and does plot in Group A. Sample ABK15 (from kimberlite K91) is located farther toward the evolved end of, and slightly off, the kimberlite trend line toward high Cr loading. Sample ABK8 (kimberlite K11) is located farther toward the primitive end of the kimberlite trend line. Samples from kimberlite TQ155, which contained relatively fewer diamonds (30 microdiamonds [<0.05 mm] from a 275 kg. sample; Ashton Mining of Canada Inc., 1999b) than kimberlites that were bulk sampled, also plot in Group A on Figure 16. On the plot of TiO_2 versus K_2O, samples ABK08, ABK15, ABK16, ABK17 and ABK18 plot in the same grouping as samples from pipes with elevated diamond content.

Nevertheless, it should be recognized that the majority of the samples collected from pipes that contain higher diamond contents (from pipes discovered to date in Alberta), have similar major and trace element contents. Subject to minimal contamination, these data may be used as a fast economic measure for future discoveries in the Buffalo Head Hills area and possibly Alberta.

Selected major and trace elements from the diamond-bearing kimberlites are presented in Table 5. In general, the samples contain low TiO_2 (0.45–1.2 wt. %), P_2O5 (0.22–0.51 wt. %) and Nb (108–189 ppm), and high MgO (26.7–38.1 wt. %), Mg# (87–90), Cr_2O_3 (0.11–0.22 wt. %) and Ni (1007–1621 ppm). The samples also have low SiO_2 (26.8–33.5 wt. %) and very low Al_2O_3 (1.61–2.77 wt. %).

The presence of diamonds in more primitive kimberlite is not totally surprising. The high Mg#, Cr and Ni, low Al_2O_3 and SiO_2, and the presence of diamonds in the Buffalo Head Hills suggest that these kimberlites were likely derived from an asthenospheric mantle source. The lower Ni contents and enrichment in HREE and incompatible elements may indicate that the Birch Mountains were derived from a shallower, depleted mantle component that was metasomatically enriched prior to kimberlite generation. Conversely, the evolved magma and the general lack of diamonds in the Birch Mountains pipes may also suggest that the diamonds were lost during ascent or emplacement. A shallower lherzolitic source is inferred for the Mountain Lake hybrid on the basis of higher Al_2O_3 and HREE contents.

6. Conclusions

Whole-rock composition of minimally contaminated volcaniclastic pipes may be used as a tool for the classification of ultramafic rocks in northern Alberta. Because of the extremely high contents of Mg, Ni, Cr, Sr, Ba, REE, Zr and Nb relative to their abundance in common crustal rocks, crustal contamination cannot be responsible for either the observed enrichment in these elements or the compositional variation within and between intrusions.

Major- and trace-element data were used to divide Alberta kimberlitic pipes into two groups: kimberlite and a hybrid alkali ultramafic rock. The Buffalo Head Hills and Birch Mountains kimberlites have close major element geochemical affinities with Group I South African kimberlite. They can be distinguished from one another by their primitive to evolved geochemical signatures. Pipes in the Buffalo Head Hills represent the most primitive kimberlite in this dataset, based on their whole-rock composition. They contain the lowest concentrations of SiO_2, Al_2O_3, V, Y, Pb, Sr and Ga, and the highest values of MgO, Mg#, Cr and Ni. In addition, whole-rock data from the Buffalo Head Hills are similar to primitive kimberlite in this dataset, based on their whole-rock composition. They contain the lowest concentrations of SiO_2, Al_2O_3, V, Y, Pb< Sr and Ga, and the highest values of MgO, Mg#, Cr and Ni. In addition, whole-rock data from the Buffalo Head Hills are similar to primitive kimberlite from the Northwest Territories.

In contrast, the Birch Mountains kimberlites are more evolved, with lower SiO_2 and Ni and higher Fe_2O_3, TiO_2, Nb, V, Sc, Zr, Hf, Y, Ba, Rb, LREE, Ga and Pb. Samples ABK81, ABK82 and ABK83

Table 5. Selected major- and trace-element contents of samples from kimberlite pipes with elevated counts of diamond.

Element		ABK04	ABK05	ABK09	ABK10	ABK11	ABK12	ABK13	ABK16	ABK17	ABK18	ABK28	ABK29	ABK30	Minimum	Maximum	Average	ABK15
SiO_2	%	29.59	29.72	32.93	31.87	33.52	28.89	28.92	28.12	29.47	30.49	26.75	29.76	32.52	26.75	33.52	30.20	29.93
Al_2O_3	%	2.03	2.77	2.13	1.95	1.61	1.63	1.62	2.70	2.54	1.95	2.53	2.47	2.02	1.61	2.77	2.15	1.86
Fe_2O_3	%	8.89	8.94	8.97	7.84	8.36	7.66	7.77	8.33	8.62	8.55	7.07	8.06	7.86	7.07	8.97	8.22	8.17
MgO	%	33.83	32.30	36.91	34.77	37.18	29.11	29.34	31.45	35.41	38.06	26.72	27.33	31.26	26.72	38.06	32.59	33.47
CaO	%	6.57	7.54	3.58	5.42	3.64	11.76	11.48	6.08	6.02	5.41	15.31	11.78	5.73	3.58	15.31	7.72	8.19
Na_2O	%	0.06	0.04	0.08	0.03	0.08	0.09	0.09	0.11	0.09	0.07	0.03	0.15	0.10	0.03	0.15	0.08	0.06
K_2O	%	0.30	0.20	0.23	0.32	0.15	0.15	0.14	0.36	0.22	0.15	0.25	0.34	0.32	0.14	0.36	0.24	0.48
TiO_2	%	1.20	0.90	0.47	0.63	0.57	0.80	0.84	0.54	0.48	0.45	0.62	0.77	0.77	0.45	1.20	0.70	0.86
P_2O_5	%	0.22	0.50	0.25	0.43	0.41	0.47	0.51	0.44	0.41	0.38	0.28	0.37	0.49	0.22	0.51	0.40	0.93
MnO	%	0.15	0.16	0.14	0.12	0.13	0.11	0.10	0.14	0.14	0.14	0.12	0.15	0.13	0.10	0.16	0.13	0.15
Cr_2O_3	%	0.22	0.16	0.14	0.14	0.13	0.14	0.15	0.15	0.15	0.15	0.11	0.14	0.16	0.11	0.22	0.15	0.18
LOI	%	16.70	16.10	13.80	15.90	13.80	18.60	18.70	21.20	15.90	13.60	19.80	17.80	18.00	13.60	21.20	16.92	14.90
Total	%	99.72	99.53	99.92	99.66	99.83	99.67	99.93	99.83	99.72	99.69	99.79	99.34	99.64	99.34	99.93	99.71	99.54
C.I.		0.92	0.99	0.94	0.96	0.94	1.04	1.03	0.96	0.90	0.85	1.08	1.16	1.09	0.85	1.16	0.99	0.93
Ilm. I		0.27	0.27	0.23	0.22	0.22	0.26	0.26	0.25	0.23	0.21	0.26	0.29	0.25	0.21	0.29	0.25	0.24
Mg#		88.29	87.74	89.07	89.78	89.80	88.27	88.21	88.20	89.05	89.81	88.21	87.04	88.73	87.04	89.81	88.63	89.03
Na_2O/K_20		0.20	0.20	0.35	0.09	0.53	0.60	0.64	0.31	0.41	0.47	0.12	0.44	0.31	0.09	0.64	0.36	0.13
Ba	ppm	800.00	326.00	763.00	308.00	387.00	535.00	559.00	744.00	959.00	909.00	296.00	553.00	944.00	296.00	959.00	621.77	1437.00
Ni	ppm	1279.00	1251.00	1559.00	1601.00	1621.00	1524.00	1562.00	1007.00	1296.00	1429.00	1343.00	1189.00	1376.00	1007.00	1621.00	1387.46	1571.00
Sc	ppm	12.00	13.00	6.00	9.00	8.00	10.00	10.00	11.00	10.00	10.00	9.00	12.00	10.00	6.00	13.00	10.00	11.00
Co	ppm	90.20	87.40	96.60	86.90	100.10	87.30	91.40	84.50	87.20	101.70	80.80	79.60	80.70	79.60	101.70	88.80	88.60
Cs	ppm	0.10	0.20	0.50	0.50	0.20	0.30	0.30	0.80	0.50	0.20	1.50	0.50	0.30	0.10	1.50	0.45	0.40
Ga	ppm	3.20	3.20	3.70	3.40	3.10	2.60	2.10	4.60	3.90	3.80	4.20	3.90	2.90	2.10	4.60	3.43	2.70
Hf	ppm	4.10	3.10	3.90	3.70	3.40	4.10	4.50	2.30	2.00	1.60	2.80	3.20	3.90	1.60	4.50	3.28	5.80
Nb	ppm	188.60	172.30	116.80	133.00	117.10	158.30	172.50	135.70	121.20	120.20	108.30	130.10	147.20	108.30	188.60	140.10	208.80
Rb	ppm	1.10	7.60	15.50	14.10	6.00	6.60	6.10	22.60	10.00	5.20	10.30	26.50	14.60	1.10	26.50	11.25	22.60
Sr	ppm	137.90	419.20	601.30	624.30	336.80	737.30	773.70	566.30	691.20	646.80	450.80	789.30	1162.30	137.90	1162.30	610.55	1301.10
Ta	ppm	17.80	12.60	7.10	9.60	8.20	11.30	12.50	9.40	8.20	8.50	8.50	9.80	10.70	7.10	17.80	10.32	12.70
Th	ppm	30.90	23.20	14.70	19.00	15.40	20.50	22.90	26.30	22.40	22.30	15.10	18.10	20.60	14.70	30.90	20.88	23.90
U	ppm	3.30	3.90	3.80	4.30	3.30	4.70	4.60	3.10	3.00	3.00	2.90	3.10	4.30	2.90	4.70	3.64	4.80
V	ppm	39.00	66.00	57.00	44.00	41.00	51.00	53.00	77.00	75.00	69.00	64.00	125.00	73.00	39.00	125.00	64.15	65.00
Zr	ppm	129.10	120.80	141.80	138.60	124.60	162.20	175.00	88.90	87.50	78.50	107.00	111.90	157.40	78.50	175.00	124.87	246.30
Y	ppm	11.70	10.90	5.40	10.10	8.70	10.40	11.10	7.20	6.90	6.40	9.10	9.20	10.60	5.40	11.70	9.05	12.90
La	ppm	194.70	163.60	101.00	141.30	118.40	163.70	176.40	145.10	128.20	107.90	109.90	133.70	159.90	101.00	194.70	141.83	210.50
Ce	ppm	392.90	303.70	172.90	283.40	232.60	312.50	341.80	262.10	229.60	190.30	212.20	247.50	313.70	172.90	392.90	268.86	400.20
Nd	ppm	130.50	97.20	48.70	91.50	77.20	105.80	112.60	70.00	58.00	52.20	69.10	82.10	102.60	48.70	130.50	84.42	134.90
Yb	ppm	0.71	0.66	0.40	0.57	0.52	0.58	0.63	0.52	0.49	0.47	0.65	0.56	0.64	0.40	0.71	0.57	0.69
Mo	ppm	1.00	1.00	1.00	< 1	1.00	1.00	< 1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Cu	ppm	22.00	48.00	10.00	24.00	26.00	32.00	32.00	25.00	22.00	21.00	19.00	36.00	30.00	10.00	48.00	26.69	61.00
Pb	ppm	6.00	8.00	10.00	6.00	6.00	8.00	7.00	10.00	11.00	8.00	6.00	5.00	6.00	5.00	11.00	7.46	9.00
Zn	ppm	59.00	60.00	60.00	50.00	53.00	53.00	54.00	56.00	54.00	54.00	46.00	48.00	51.00	46.00	60.00	53.69	58.00

C.I. = Contamination index ($[SiO_2+Al_2O_3]/[2K_2O+MgO]$)

Ilm.I. = Ilmenite index ($[FeO_{total}+TiO_2]/[2K_2O+MgO]$)

Mg# = $100*MgO/(MgO+FeO_{total})$

(from the newly discovered Kendu pipe) in the Birch Mountains plot closer to the primitive magma field than those from other pipes in the Birch Mountains. Hence, the Kendu pipe contains the most primitive kimberlite in the Birch Mountains and is closer to the geochemical signature of the demonstrably diamondiferous Buffalo Head Hills kimberlites. Conversely, samples ABK75 to ABK78 from the Phoenix kimberlite contain the highest concentrations of high field-strength elements (HFSEs) and represent the most evolved kimberlite.

A linear trend is found for northern Alberta kimberlite, which reflects compositional evolution from primitive to evolved kimberlite magmas. Northern Alberta pipes with elevated contents of diamonds generally have similar chemistry and plot at the primitive end of this trend line. Exploration companies will therefore be able to compare future discoveries of kimberlite with the results of this study for a quick and economical evaluation of a prospective target.

The Mountain Lake pipes are not kimberlite, but rather a hybrid rock with geochemical affinities to basanite (olivine potassic basalt), the Sweet Grass olivine minette and Montana alnöite. Compared to northern Alberta kimberlite (Buffalo Head Hills and Birch Mountains), Mountain Lake contains higher SiO_2, Al_2O_3, Na_2O, K_2O, Na_2O/K_2O, Ga, Rb and peralkalinity index, and lower MgO, Nb, LREE, Sr, Niggli K, and Niggli mg. Mountain Lake is therefore classified as a high potassic alkali ultramafic rock.

Inter-field geochemical variations are also evident. Samples from kimberlites K4 and LL8 in the Buffalo Head Hills, and from the Kendu pipe in the Birch Mountains have significantly different geochemical properties in comparison to other samples/pipes from their respective fields, which suggest therefore, that these pipes have a different mineralogical origin.

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Appendix 1. **Preliminary (Macroscopic) Alberta Kimberlitic Rock Sample Descriptions**

Sample No.	Drillhole/ rock ID	Description
RE00-AB-K01	4A-02	Tan-brown, competent, but badly weathered[BD1]. Xenoliths of subrounded carbonate and angular shale. Chromite occurs as blebs (up to 2 mm).
RE00-AB-K02	4B-01	Light grey-green, competent. Bitumen-stained; intermixed within a fractionated matrix. Black, angular shale clasts (up to 1.3 cm); possible smaller carbonate clasts.
RE00-AB-K03	4C-01	Tan to green-yellow, medium grained, and highly altered with a vuggy appearance. Matrix dominates sample (up to 60 vol. %) and is highly altered (carbonate and silica); conspicuous grains possibly quartz pebbles.
RE00-AB-K04	5A-02	Light green-grey, competent and fine to medium grained. Some orange alteration of olivine micro- and macrocrysts. Shale dominant crustal material.
RE00-AB-K05	6-02	Light grey-green (fairly fresh) pelletal-lapilli (between 0.1 and 11 mm) characterized by altered olivine cores (some with trace sulphide - magnetite?) and dark green serpentinized rims. Most lapilli are orientated horizontally, but some (10%) are vertical or tilted.
RE00-AB-K06	7B-01	Green with a dark green matrix. Olivine-rich phenocrysts (generally 2 mm) are rounded with fractured, altered (carbonate) cores. Up to 7 vol. % country rock xenoliths (shale > silty shale > carbonate).
RE00-AB-K07	7C-01	Buff, rubbly, and altered (original texture difficult to discern). Subrounded quartz grains (up to 15 vol. % and up to 2 mm in size) suggest a siltstone or sandstone component. Relict olivine macrocrysts or lapilli are completely altered to clay minerals.
RE00-AB-K08	11-01	Green-grey, fine to medium grained, fresh, pale green[BD2] olivine. High concentration (>15 vol. %) of segregated xenoliths of mantle material (pyrope and eclogite garnet, ilmenite).
RE00-AB-K09	11-01	Dark grey-green. Olivine macrocrysts and phenocrysts are darker (serpentinite?) and vary in texture from rounded to blocky and broken. Crustal basement xenolith (gneiss).
RE00-AB-K10	14-01	Grey-green. Abundant segregated lapilli (up to 50 vol. %) are rounded, rimmed with a thin continuous layer of serpentinite and contain fractured inner cores that appear to be altered to clay (and commonly contain magnetite?).
RE00-AB-K11	14B-03	Dark grey-green with soapy feel. Altered olivine macrocrysts dominate (40 vol. %) Variable size and alteration: most are altered dark green (serpentinite) or white (calcite). Fine grained, serpentinized, carbonatized olivine matrix (40 vol. %).
RE00-AB-K12	14C-06	Light grey-green (fresh), competent. Matrix dominated; very fine-grained (aphanitic appearance) olivine with altered macrocrystalline olivine (up to 9 mm).
RE00-AB-K13	14C-06	Duplicate of RE00-AB-K12.
RE00-AB-K14	19-03	Dark grey-green, rubbly, soapy feel. Olivine macrocrysts and rounded, possible lapilli are highly altered to clay minerals. Coarse-grained matrix consists of altered (serpentine and carbonate) olivine phenocrysts and macrocrysts.
RE00-AB-K15	91-03	Green-grey kimberlite. Olivine lapilli dominate; their size and appearance vary (average about 6 mm, largest is 9 mm). Lapilli are serpentinized and some are autolithic. Carbonatized olivine matrix.
RE00-AB-K16	155-01	Grey-green. Bitumen-rich (along fractures and overtaking fractured olivine cores). Bitumen has only altered about 50% of the olivine grains, indicating that there may have been separate events.
RE00-AB-K17	155-01	Light green-grey. Main characteristic is the totally bitumen-stained olivine microcrysts, macrocrysts and lapilli.
RE00-AB-K18	155-01	Duplicate of RE00-AB-K17.
RE00-AB-K19	BM2-01	Light grey-brown, fairly competent siltstone occurring between overburden and intersection of kimberlite. Some distorted (angular) bedding observed; this may indicate slumping.
RE00-AB-K20	BM2-01	Light grey-green. Olivine lapilli and macrocrysts are completely altered to either black serpentine or a material whose composition is difficult to distinguish. Matrix is highly carbonatized, giving the sample its bleached appearance. Three carbonate veins; largest is 2 to 4 mm in width.
RE00-AB-K21	BM2-01	Dark grey-blue, very competent, aphanitic matrix, olivine megacrysts are metasomatized (black in appearance). Xenolith concentrations are completely altered and occur as rounded (many still anhedral) black xenoliths; some (< 40%) have calcite in the core. Carbonate xenoliths are waxy green in colour and constitute approximately 8 vol. %. Some carbonate veinlets (<2 mm in width).
RE00-AB-K22	BM2-01	Dark blue-grey, competent. Dark, aphanitic matrix with calcite replacement (up to 8 vol. %); calcite also occurs in segregations. Xenoliths (olivine?) are completed altered to dark serpentinite (up to 15 vol. %). Black angular shale clasts (up to 3 vol.%) are rimmed with calcite.
RE00-AB-K23	BM3-01	Medium grey-green with abundant shale xenoliths and rounded juvenile lapilli. Alteration is pervasive throughout and nearly all primary textures have been destroyed. Largest shale clast is 2.4 by 1.1 cm; sharp contacts with no alteration to slightly strung out and swirled clasts.
RE00-AB-K24	BM3-01	Medium grey-green with abundant shale and carbonate (or siltstone?); alteration is pervasive [BD3]and nearly all primary textures are destroyed. Abundant olivine lapilli phenocrysts (55 vol. %). Carbonate and olivine pseudomorph-rich matrix. Largest carbonate (?) clast is 2.8 by 1.9 cm; alteration rims and shearing are evident in carbonate clasts.
RE00-AB-K25	LL8-01	White, bleached, salt and pepper, tuffaceous appearance. Olivine phenocrysts (<2 mm) altered to serpentinite and carbonate. Blackish brown clasts include relatively minor, small shale clasts (2 vol. %),

Appendix 1. Preliminary (Macroscopic) Alberta Kimberlitic Rock Sample Descriptions

Sample No.	Drillhole/ rock ID	Description
		bitumen (5 vol. %) and brown mica (3 vol. %).
RE00-AB-K26	LL8-01	Yellow-green. Dominated by pseudomorphed or partially fresh olivine macrocrysts (up to 3 mm). Macrocrysts are typically altered to a carbonate orange-brown colour; but a fair amount of fresh pale green olivine is present. Matrix is very unusual in this sample; yellow-green due to serpentinization.
RE00-AB-K27	LL8-01	Light grey-green; highly bleached. Medium- to coarse-grained crystalline olivine, which is highly altered and serpentinized. Sample contains only very rare olivine macrocrysts (vary from fresh to completely altered). Olivine crystals are 'mixed' with fine- to medium-grained quartz grains (up to 15 vol. %); also some carbonate and shale xenoliths (small, usually <8 mm).
RE00-AB-K28	K5 (surface)	Dark grey-black, competent with pervasive carbonate alteration. Fresh (dominate) and relict olivine macrocrysts; lapilli are highly altered (serpentinized). Matrix is very fine and dark coloured (serpentinized). Carbonate (calcite) occurs in both veins and rimming xenoliths. Abundant carbonate and shale xenoliths.
RE00-AB-K29	K6 (surface)	Dark grey-green, competent with pervasive carbonate alteration. Fresh olivine microcrysts and macrocrysts (up to 3 mm) comprise altered cores[BD4]. Matrix is dark (serpentinized) and characterized by contrasting white calcitic alteration (preferential to fractures?). Both country rock and altered mantle xenoliths found on surface.
RE00-AB-K30	K14 (surface)	Green-grey, competent kimberlite. Abundant fresh and relict olivine macrocrysts and lapilli. Some macrocrysts and lapilli have altered cores (calcite and magnetite). Matrix is a distinct green-grey and consists of fine-grained fresh olivine (unlike other samples of kimberlite in BBH[BD5]). Very few country-rock xenoliths. High relative percentage of phlogopite flakes (5 vol. %). Perhaps one of the freshest kimberlite samples; very little carbonate or serpentine alteration observed.
RE00-AB-K31	ML95-1	Dark green-brown matrix with light grey-green (secondary) pseudomorphed olivine. Weathered and slightly oxidized. Moderate quartz-feldspar contamination.
RE00-AB-K32	ML95-1	Dark green-brown massive volcanic rock. Poorly sorted, medium-grained, ash-rich. Highly contaminated by quartz and feldspar with angular clasts of green Wapiti sandstone (up to 4 cm). Some wood debris.
RE00-AB-K33	ML95-1	Duplicate of RE00-AB-K32.
RE00-AB-K34	ML95-1	Dark green-brown volcanic rock, medium grained, massive with minor lapilli. Highly contaminated with Wapiti (quartz and feldspar xenocrysts) and Kaskapau shale clasts.
RE00-AB-K35	ML95-1	Dark green-brown volcanic rock, medium grained, but fining upwards. Olivine-rich with rare lapilli. Medium to high quartz and feldspar contamination (Wapiti).
RE00-AB-K36	ML95-1	Dark green-brown massive volcanic rock (some coarse-grained beds). Olivine-rich, rare lapilli. Variable matrix contamination (quartz and feldspar Wapiti) with xenoliths of Wapiti (up to 10 cm).
RE00-AB-K37	ML95-1	Duplicate of RE00-AB-K36.
RE00-AB-K38	ML95-1	Dark green-brown volcanic rock. Olivine-rich, rare lapilli. Abundant quartz and feldspar (Wapiti) clasts (<2 mm).
RE00-AB-K39	ML95-3	Dark green-brown volcanic rock, coarse- to medium-grained bedding. Rare lapilli. Rare indicator minerals present (garnet, clinopyroxene). Some large (up to 10 cm) Wapiti sandstone clasts.
RE00-AB-K40	ML95-3	Dark green-brown volcanic rock, coarse grained, poorly sorted. Rare autoliths (up to 4 cm) and lapilli. Abundant shale and sandstone xenoliths.
RE00-AB-K41	ML95-3	Dark green-brown volcanic rock, poorly sorted, generally coarse grained. Relict autoliths (up to 1 cm). Abundant shale and sandstone xenoliths (up to 1 cm).
RE00-AB-K42	ML95-3	Duplicate of RE00-AB-K41.
RE00-AB-K43	ML95-3	Dark green-brown volcanic rock, massive, coarse grained. Shale and Wapiti sandstone clasts (up to 3 cm).
RE00-AB-K44	ML95-3	Dark green-brown volcanic rock, moderately well sorted, very coarse grained, olivine rich. Mixed autolith and lapilli tuff (clast supported).
RE00-AB-K45	ML95-3	Dark green-brown volcanic rock, massive, poorly sorted, very coarse grained. Olivine rich. Clast and matrix supported. Shale and Wapiti clasts (up to 3 cm). Moderate indicator minerals. Wood fragments.
RE00-AB-K46	ML95-3	Dark green-brown volcanic rock, massive, moderate sorting, coarse grained. Matrix supported olivine and lapilli.
RE00-AB-K47	ML95-3	Duplicate of RE00-AB-K46.
RE00-AB-K48	98DH-XE01	Contact between aphanitic and epiclastic (?) material. Epiclastic rock is light grey-green, serpentinized with relict olivine. Contact between the light green-grey and aphanitic unit is highly altered; characterized by a white, sulphide-rich, carbonate (?) halo. Clasts of the aphanitic material are observed in the lighter kimberlite and also form a sulphide halo. Calcite veinlets splay outward from the contact and are easily recognized in the darker aphanitic material.
RE00-AB-K49	98DH-XE01	Dark grey to black with mudstone; broken and crumbly. Muddy matrix similar to Mountain Lake Diatreme samples. Abundant relict olivine; olivine is totally replaced by buff to white carbonate.
RE00-AB-K50	98DH-XE01	Duplicate of RE00-AB-K49.
RE00-AB-K51	98DH-R001	Dark grey mudstone with mudstone-supported relict olivine crystals (very crumbly). Sampled just downhole (2 m) from alternating sandstone and mudstone (sandstone dominant). Some country rock xenoliths including black, blocky shale (Westgate?).
RE00-AB-K52	98DH-PH02	Dark green, competent with dense fresh and altered olivine lapilli. Carbonate veining and alteration.

Appendix 1. Preliminary (Macroscopic) Alberta Kimberlitic Rock Sample Descriptions

Sample No.	Drillhole/ rock ID	Description
		looks like mudstone constituents. Carbonate alteration throughout. Some rusty weathering observed.
ABK54	98DH-PE01	Duplicate of ABK53.
ABK55	98DH-PE01	Black, blocky shale; does not look kimberlitic at all.
ABK56	98DH-PE01	Dark grey, competent, fine-grained kimberlite with fresh olivine macrocrysts. Fine-grained matrix is darker (serpentinized). Sugary appearance indicative of carbonate replacement. Minor country rock xenoliths; one small angular shale clast.
ABK57	98DH-LE01	Grey-green fragmental rock (dark grey matrix), competent and coarse grained. Dominated by microcrystalline and macrocrystalline olivine (trace lapilli); while some fresh olivine is present, it is typically altered and relict olivine is severely carbonatized with some Fe staining. Dark green, serpentinized matrix. Rounded to subrounded greenish white limestone (up to 5 mm in length) and angular shale (generally <4 mm).
ABK58	98DH-LE01	Grey-green, competent kimberlite (dark green aphanitic matrix). Similar to K57, but less olivine; olivine is mainly confined to the matrix and is fine grained. Matrix supported; aphanitic, serpentinized.
ABK59	98DH-LE01	Grey-green, competent kimberlite (dark green aphanitic matrix); similar to K58. Contains some fresh and partially altered (carbonate and Fe-stained) crystal olivine. Matrix supported; aphanitic, serpentinized. Ilmenite (up to 5%) and sulphide (locally up to 10%).
ABK60	98DH-LE01	Duplicate of ABK59.
ABK61	98DH-LE01	Grey-green, competent kimberlite (dark green aphanitic matrix). Contains some fresh and partially altered (carbonate and Fe-stained) crystal olivine. Matrix supported; aphanitic, serpentinized.
ABK62	98DH-LE01	Grey-green competent kimberlite (dark green aphanitic matrix). Contains some fresh and partially altered (carbonate and Fe-stained) crystal olivine. Matrix supported; aphanitic, serpentinized.
ABK63	98DH-LE01	Light grey, incompetent and crumbly kimberlite and sandstone. Bedding present between ash tuff and subrounded to rounded, medium-grained, quartz-rich sandstone. Olivine phenocrysts are completely altered to buff-white powdery remnants.
ABK64	98DH-LE01	Very similar to K58, but contains even less olivine (suspect higher silica content in this sample). Grey-green, competent kimberlite (dark green aphanitic matrix). Olivine crystals are completely altered. Matrix supported; aphanitic, serpentinized.
ABK65	98DH-LE01	Very similar to K64, but contains a slightly higher volume of country rock xenoliths. Grey-green, competent kimberlite (dark green aphanitic matrix). Olivine crystals are completely altered. Matrix supported; aphanitic, serpentinized.
ABK66	98DH-LE01	Very similar to K64 (suspect higher silica content in this sample). Grey-green, competent kimberlite (dark green aphanitic matrix). Olivine crystals are completely altered. Some accretionary lapilli present. Matrix supported; aphanitic, serpentinized.
ABK67	98DH-LE01	Similar to K66 with abundant accretionary lapilli. Grey-green, competent kimberlite (dark green aphanitic matrix). Olivine crystals are completely altered. Matrix supported; aphanitic, serpentinized.
ABK68	98DH-LE01	Light grey, competent, very fine grained, aphanitic. Olivine only present in the matrix and not as phenocrysts (like previous Legend core samples) or macrocrysts. Numerous xenoliths: angular shale, rounded carbonate, different blue hue on some fine-grained silty xenoliths.
ABK69	98DH-LE01	Light grey to buff, rusty weathering, competent. Abundant rounded quartz grains (sandstone? rock may also be silicified). Volcanic grains are totally altered and difficult to discern. Some massive sulphide confined to veinlets.
ABK70	98DH-LE01	Duplicate of ABK69.
ABK71	98DH-VA01B	Dark green-black, competent, coarse-grained, fragmental rock. Minor olivine lapilli with altered (serpentinized) cores. Matrix comprised of coarse-grained olivine crystals (with a 'welded' appearance?). Abundant country rock xenoliths; dominantly angular, black shale clasts up to 1.1 cm. Disseminated sulphide present (<5%).
ABK72	98DH-VA02	Rusty weathered, dark brown, competent, fine grained. No macrocrysts or lapilli. Matrix is altered, finely crystalline olivine. A single carbonate stringer (<1 mm wide) and abundant fine- to medium-grained crystalline calcite (?).
ABK73	98DH-VA02	Blue-grey, competent, medium- to coarse-grained fragmental rock. Distinct blue-green colouring. Trace (<1 vol. %) serpentinized olivine macrocrysts. Abundant relict and partially replaced olivine crystals. Abundant calcite in matrix and outlining olivine crystals. Subangular shale and carbonate clasts.
ABK74	98DH-VA02	Dark grey-green, competent, coarse grained. Less weathering than previous 98DH-VA02 samples. Relict and partly replaced olivine crystals.
ABK75	98DH-PH-01	Grey-green, competent, medium grained. Fresh and iron-weathered olivine macrocrysts. Fine-grained, grey-green matrix. Abundant (~5 vol. %) phlogopite. Minimal country rock xenoliths; dominantly grey clay and mudstone.
ABK76	98DH-PH-01	Dark grey, competent, fine- to medium-grained tuffaceous rock with altered and relatively fresh olivine macrocysts. Phlogopite (up to 8 vol. %) is very characteristic of this sample. Matrix is generally fine grained and appears carbonatized.
ABK77	98DH-PH-01	Light grey, competent, medium-grained tuffisitic rock. Altered, with a large percentage of fresh olivine macrocrysts. Abundant phlogopite (up to 4 vol. %). More country rock xenoliths than previous samples (~5 vol. %); dominantly subrounded grey-green carbonate and angular black shale.
ABK78	98DH-PH-01	Blue to dark grey-black, competent, autolithic. Relict olivine macrocrysts are completely carbonatized. Matrix is carbonatized, very blue and smectitic in appearance. Dominantly carbonate country-rock

Appendix 1. Preliminary (Macroscopic) Alberta Kimberlitic Rock Sample Descriptions

Sample No.	Drillhole/ rock ID	Description
		Matrix is carbonatized, very blue and smectitic in appearance. Abundant autoliths (~10 vol. %). Dominantly carbonate country-rock xenoliths.
RE00-AB-K79	98DH-PH-01	Grey-green, competent, autolithic tuff. Abundant dark grey autoliths; carbonatized; autoliths up to 1.8 cm. Lighter green-grey matrix comprising fine- to medium-grained olivine and minor relict olivine macrocrysts. Country rock xenoliths are dominantly blue-green marl.
RE00-AB-K80	LE (surface)	Highly oxidized (brown-red), fine-grained tuff. Few olivine macrocrysts (typically relict). Matrix is finely crystalline and appears silicified (?). Abundant country rock xenoliths; dominantly shale clasts.
RE00-AB-K81	Kendu	Light grey-green, fairly competent fragmental rock. Abundant relict (white to buff-white) olivine macrocrysts and lapilli; lapilli comprise fresh ashy material and fresh to altered crystal olivine. Lapilli appear to be altered to clay; the macrocrysts occasionally dominate and are not matrix supported. Matrix is fine grained to aphanitic, darker grey-green and carbonatized. Eclogitic mantle xenolith (1.65 by 1.25 cm) consisting of olivine and eclogitic garnets. Fresh olivine macrocrysts, phlogopite, and eclogitic and pyrope garnets are randomly distributed throughout the sample. Angular, stretched and sometimes broken or sheared shale xenoliths (up to 10 vol. %).
RE00-AB-K82	Kendu	Light grey-green, fairly competent fragmental rock. Relict olivine macrocrysts (white to buff-white), typically replaced by calcite and magnetite (inner cores). Matrix is grey-green and highly carbonatized. Eclogitic mantle xenolith (2.3 by 0.9 cm) consisting of olivine and eclogitic garnets; also several smaller (<0.5 cm) xenoliths; one sample for thin section and many DIMs (eclogitic and pyrope garnet, ilmenite, kyanite (?); very little to no clinopyroxene). Country-rock xenoliths include both rounded and subangular shale (<8 vol. %) and carbonate (<5 vol. %) clasts.
RE00-AB-K83	Kendu	Green-grey to black, competent, fragmental rock. Relict olivine macrocrysts are altered to white to buff-white. Some autoliths. Matrix is dark green and carbonatized. Large (3.5 by 2.1 cm) mantle xenolith. DIMs picked include ilmenite, clinopyroxene, pyrope and eclogitic garnet.

Appendix 2. Major-Element Geochemical Data From Bulk Rock Samples Collected From Selected Pipes in the Mountain Lake, Buffalo Head Hills and Birch Mountains Areas.

Sample No.	Drillhole/ surface sample	Sample depth	UTM Easting	UTM Northing	UTM Zone	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	MnO (%)	Cr_2O_3 (%)	Ba (ppm)	Ni (ppm)	Sc (ppm)	LOI (%)	C_{tot} (%)	S_{tot} (%)	SUM (%)	Contam. Index	Ilmenite Index
Detection limit						0.02	0.03	0.04	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.001	5	20	10						
Buffalo Head Hills																									
ABK01	4A-02	49.15	578380	6301519	11	36.89	0.17	3.47	27.59	1.02	0.09	0.3	0.01	0.12	0.05	0.115	133	611	2	30	8.27	0.02	99.55	1.318	0.111
ABK02	4B-01	140.65	578464	6300991	11	31.67	0.62	7.87	42.84	3.97	0.09	0.1	0.07	0.29	0.12	0.197	356	1535	4	11.9	3.46	1.03	99.88	0.752	0.166
ABK03	4C-01	63.00	578821	6301274	11	28.5	0.63	5.91	38.77	1.58	0.01	0.06	0.08	0.3	0.1	0.129	157	1309	7	23.6	3.9	0.07	99.85	0.749	0.139
ABK04	5A-02	84.23	582687	6306035	11	29.59	2.03	8.89	33.83	6.57	0.06	0.3	1.2	0.22	0.15	0.221	800	1279	12	16.7	1.07	0.25	99.72	0.920	0.257
ABK05	6-02	110.15	585550	6308383	11	29.72	2.77	8.94	32.3	7.54	0.04	0.2	0.9	0.5	0.16	0.158	326	1251	13	16.1	1.74	0.22	99.53	0.995	0.274
ABK06	7B-01	76.93	583131	6312089	11	22.29	3.47	9.08	18.03	15.48	0.4	0.46	1.24	0.63	0.17	0.09	1503	581	14	28	6.29	0.26	99.58	1.380	0.497
ABK07	7C-01	58.40	583052	6312455	11	12.66	2.99	7.64	14.02	23.09	0.21	0.17	1.44	0.7	0.17	0.103	1120	437	17	36.2	9.41	0.03	99.58	1.104	0.579
ABK08	11-01	55.50	619724	6320041	11	34.78	1.43	9.51	40.94	1.52	0.02	0.16	0.8	0.16	0.12	0.115	683	1702	7	10.1	0.57	0.13	99.95	0.878	0.227
ABK09	11-01	135.50	619724	6320041	11	32.93	2.13	8.97	36.91	3.58	0.08	0.23	0.47	0.25	0.14	0.142	763	1559	6	13.8	1.25	0.06	99.92	0.940	0.229
ABK10	14-01	14.56	582883	6315050	11	31.87	1.95	7.84	34.77	5.42	0.03	0.32	0.63	0.43	0.12	0.139	308	1601	9	15.9	1.25	0.06	99.66	0.956	0.217
ABK11	14B-03	30.17	582820	6315277	11	33.52	1.61	8.36	37.18	3.64	0.08	0.15	0.57	0.41	0.13	0.133	387	1621	8	13.8	0.91	0.33	99.83	0.939	0.216
ABK12	14C-06	54.30	583030	6315357	11	28.89	1.63	7.66	29.11	11.76	0.09	0.15	0.8	0.47	0.11	0.142	535	1524	10	18.6	2.69	0.17	99.67	1.041	0.262
ABK13	**14C-06**	**54.30**	**583030**	**6315357**	**11**	**28.92**	**1.62**	**7.77**	**29.34**	**11.48**	**0.09**	**0.14**	**0.84**	**0.51**	**0.1**	**0.153**	**559**	**1562**	**10**	**18.7**	**2.62**	**0.14**	**99.93**	**1.034**	**0.264**
ABK14	19-03	19.85	575034	6289104	11	41.35	5.93	5.7	19.83	7.06	0.08	1.54	0.46	0.47	0.09	0.092	1325	947	10	17	1.73	0.06	99.87	2.067	0.244
ABK15	91-03	84.93	581820	6317052	11	29.93	1.86	8.17	33.47	8.19	0.06	0.48	0.86	0.93	0.15	0.179	1437	1571	11	14.9	2.04	0.31	99.54	0.925	0.238
ABK16	155-01	102.50	581763	6293954	11	28.12	2.7	8.33	31.45	6.08	0.11	0.36	0.54	0.44	0.14	0.146	744	1007	11	21.2	8.31	0.43	99.83	0.961	0.250
ABK17	155-01	148.60	581763	6293954	11	29.47	2.54	8.62	35.41	6.02	0.09	0.22	0.48	0.41	0.14	0.146	959	1296	10	15.9	5.89	0.32	99.72	0.895	0.230
ABK18	**155-01**	**148.60**	**581763**	**6293954**	**11**	**30.49**	**1.95**	**8.55**	**38.06**	**5.41**	**0.07**	**0.15**	**0.45**	**0.38**	**0.14**	**0.151**	**909**	**1429**	**10**	**13.6**	**5.58**	**0.31**	**99.69**	**0.847**	**0.212**
ABK19	BM2-01	52.00	632349	6309823	11	70.12	11.53	4.32	1.9	1.36	1	1.94	0.62	0.18	0.03	0.014	1138	45	10	6.3	1.31	0.25	99.45	14.299	0.780
ABK20	BM2-01	79.50	632349	6309823	11	25.55	3.36	6.64	19.66	19.81	0.37	2.47	1.03	0.64	0.12	0.143	2494	791	12	19.7	4.34	0.55	99.87	1.190	0.285
ABK21	BM2-01	103.30	632349	6309823	11	28.36	2.62	9.03	32.23	7.82	0.11	0.23	1.4	0.89	0.19	0.2	2284	1143	16	15.8	1.02	0.21	99.28	0.951	0.291
ABK22	BM2-01	113.80	632349	6309823	11	27.47	2.81	8.18	29.45	12.03	0.14	0.25	1.32	0.96	0.17	0.182	2704	990	15	16.5	2.01	0.2	99.89	1.016	0.290
ABK23	BM3-01	124.90	631219	6314208	11	40.79	5.86	5.53	19.59	7.24	0.1	1.49	0.45	0.49	0.09	0.103	1386	1122	10	17.5	1.77	0.05	99.53	2.071	0.240
ABK24	BM3-01	144.90	631219	6314208	11	38.87	8.61	6.83	11.2	11.86	2.38	3.86	1.05	0.64	0.09	0.055	2474	245	16	13.4	2.78	0.09	99.15	2.635	0.380
ABK25	LL8-01	77.80	629936	6301692	11	17.24	0.41	4.56	33.66	2.97	0.06	0.25	0.05	0.15	0.07	0.128	274	1213	3	39.7	11.11	0.05	99.43	0.518	0.122
ABK26	LL8-01	121.50	629936	6301692	11	36.26	1.11	7.92	40.9	0.75	0.03	0.19	0.06	0.22	0.1	0.156	77	2091	4	11.7	0.54	0.16	99.67	0.906	0.174
ABK27	LL8-01	144.90	629936	6301692	11	35.39	0.66	8.23	44.94	1.6	0.02	0.4	0.07	0.32	0.13	0.168	158	2171	6	7.7	0.73	0.13	99.92	0.789	0.163
ABK28	K5 (surface)	surface O/C	582432	6306145	11	26.75	2.53	7.07	26.72	15.31	0.03	0.25	0.62	0.28	0.12	0.109	296	1343	9	19.8	3.18	0.41	99.79	1.077	0.256
ABK29	K6 (surface)	surface O/C	585317	6308651	11	29.76	2.47	8.06	27.33	11.78	0.15	0.34	0.77	0.37	0.15	0.144	553	1189	12	17.8	2.62	< .01	99.34	1.156	0.286
ABK30	K14 (surface)	surface O/C	582894	6315185	11	32.52	2.02	7.86	31.26	5.73	0.1	0.32	0.77	0.49	0.13	0.156	944	1376	10	18	2.18	< .01	99.64	1.086	0.246
Mountain Lake Diatreme																									
ABK31	ML95-1	7.22	454636	6145914	11	50.41	9.73	6.26	12.83	3.32	0.92	2.17	0.92	0.31	0.1	0.109	914	406	14	12.2	0.63	< .01	99.43	3.556	0.382
ABK32	ML95-1	35.00	454636	6145914	11	59.21	11.15	5.92	7.42	2.68	2.31	2.93	0.76	0.23	0.09	0.057	992	204	12	6.9	0.87	0.37	99.8	5.472	0.458
ABK33	**ML95-1**	**35.00**	**454636**	**6145914**	**11**	**59.99**	**11.49**	**5.44**	**6.97**	**2.67**	**2.29**	**3.1**	**0.79**	**0.22**	**0.08**	**0.062**	**1044**	**271**	**13**	**6.7**	**9.01**	**2.91**	**99.95**	**5.601**	**0.432**
ABK34	ML95-1	64.00	454636	6145914	11	31.96	6.56	3.62	2.45	27.55	1.33	1.03	0.56	0.44	0.22	0.053	1131	236	11	23.6	6.44	0.77	99.53	8.836	0.846
ABK35	ML95-1	95.00	454636	6145914	11	56.53	10.85	6.06	8.62	3.81	2.27	2.45	0.89	0.3	0.1	0.083	909	286	14	7.6	0.9	0.29	99.7	5.152	0.469
ABK36	ML95-1	134.10	454636	6145914	11	61.24	11.23	5.26	6.46	2.96	2.66	2.16	0.75	0.22	0.09	0.058	911	204	13	6.2	0.82	0.12	99.42	6.969	0.509
ABK37	**ML95-1**	**134.10**	**454636**	**6145914**	**11**	**61.61**	**11.35**	**5.38**	**6.48**	**2.71**	**2.55**	**2.15**	**0.73**	**0.2**	**0.09**	**0.056**	**945**	**197**	**13**	**6.1**	**0.72**	**0.14**	**99.54**	**7.005**	**0.517**
ABK38	ML95-1	161.90	454636	6145914	11	49.49	9.59	6.79	13.26	4.32	2.29	2.12	0.92	0.33	0.12	0.114	984	508	15	10	0.91	0.3	99.52	3.507	0.402
ABK39	ML95-3	7.45	454779	6145324	11	47.64	8.4	6.57	15.06	5.09	1.15	2.29	0.84	0.29	0.11	0.115	933	562	13	12.1	0.67	0.21	99.83	2.912	0.344
ABK40	ML95-3	29.80	454779	6145324	11	48	9.07	6.34	14.18	4.86	1.7	2.17	0.85	0.28	0.11	0.105	2641	479	13	11.7	0.74	0.21	99.72	3.173	0.354
ABK41	ML95-3	60.00	454779	6145324	11	46.2	7.58	7.78	16.39	4.4	1.35	1.71	0.79	0.29	0.11	0.135	837	712	12	12.6	0.68	0.21	99.52	2.783	0.393
ABK42	ML95-3	60.00	454779	6145324	11	47.14	7.89	7.18	15.75	4.72	1.39	2.16	0.85	0.31	0.11	0.137	915	721	13	11.9	0.68	0.24	99.73	2.811	0.364
ABK43	ML95-3	88.80	454779	6145324	11	45.98	7.46	6.95	16.74	5.01	1.37	1.65	0.85	0.31	0.12	0.138	829	701	13	13	0.68	0.21	99.76	2.735	0.354
ABK44	ML95-3	117.90	454779	6145324	11	47.08	8.31	6.79	15.53	4.75	1.43	2.24	0.84	0.3	0.12	0.13	971	601	13	12.2	0.78	0.33	99.91	2.840	0.347
ABK45	ML95-3	133.90	454779	6145324	11	47.09	8.64	6.63	16.22	3.86	1.61	1.98	0.86	0.31	0.12	0.115	913	580	14	11.8	0.67	0.14	99.41	2.841	0.338
ABK46	ML95-3	165.00	454779	6145324	11	51.37	9.29	6.43	13.71	3.24	1.92	2.44	0.89	0.3	0.1	0.119	959	507	14	9.6	0.6	0.22	99.58	3.366	0.359
ABK47	ML95-3	165.00	454779	6145324	11	51.51	9.42	6.39	13.43	3.21	1.83	2.58	0.89	0.28	0.1	0.116	990	467	14	9.6	0.64	0.24	99.53	3.376	0.357
Birch Mountains																									
ABK48	98DH-XE01	87.70	376850	6347300	12	17.33	5.41	7.9	4.51	27.97	0.34	2.47	1.36	0.91	0.23	0.093	3034	589	14	23	7.17	4.52	91.94	2.442	0.896
ABK49	98DH-XE01	153.96	376850	6347300	12	48.52	9.34	7.11	13.53	3.86	1.73	2.56	1.41	0.44	0.07	0.076	1344	355	14	11	1.48	0.48	99.84	3.195	0.419
ABK50	98DH-XE01	153.96	376850	6347300	12	49.1	9.38	7	13.23	3.49	1.81	2.26	1.39	0.45	0.07	0.075	1114	337	14	11.4	1.42	0.5	99.82	3.397	0.433
ABK51	98DH-R001	123.00	365051	6357585	12	37.77	7.78	7.1	12.25	11.28	0.41	3.06	1.32	0.51	0.24	0.048	1298	230	16	17.6	3.34	0.38	99.54	2.502	0.420
ABK52	98DH-PH02	137.00	351550	6330493	12	21.33	2.7	10.05	23.79	13.66	0.15	0.33	2.65	0.7	0.18	0.119	1606	496	16	23.8	5.09	0.1	99.7	0.989	0.478
ABK53	98DH-PE01	100.00	374692	6368251	12	31.87	3.5	9.79	23.41	8.86	0.19	0.61	2.08	0.43	0.17	0.197	611	834	16	18.7	2.69	0.18	99.98	1.444	0.442
ABK54	98DH-PE01	100.00	374692	6368251	12	32.33	3.46	9.63	23.37	8.71	0.18	0.56	2.11	0.43	0.17	0.211	709	859	16	18.3	2.52	0.25	99.65	1.469	0.443

Appendix 3. Trace-Element Geochemical Data From Bulk Rock Samples Collected From Selected Pipes in the Mountain Lake, Buffalo Head Hills and Birch M

Sample No.	Drillhole ID	Depth (m)	UTM Easting	UTM Northing	UTM Zone	Co (ppm)	Ce (ppm)	Ga (ppm)	Hf (ppm)	Nb (ppm)	Rb (ppm)	Sn (ppm)	Sr (ppm)	Ta (ppm)	Th (ppm)	Ti (ppm)	U (ppm)	V (ppm)	W (ppm)	Zr (ppm)	Y (ppm)	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Mo (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Ni (ppm)	As (ppm)	Cd (ppm)	Sb (ppm)	Bi (ppm)
Detection						0.1	0.1	0.1	0.1	0.05	0.02	0.5	0.1	0.1	0.1	0.1	0.1	5	0.5	0.5	0.1	0.1	0.1	0.1	0.05	0.1	0.1	0.05	0.1	0.05	0.1	0.05	0.1	0.05	0.01	1	2	5	5	5	0.1	0.1	0.1
ABK01	4A-02	49.15	578380	6301519	11	39.2	0.1 < .5	4.5	23.1	2 < 1	238.5	1.8	5.5	0.2	1.3	17 < 1		164.5	0.7	13.1	25.2	2.29	6.9	0.8	0.19	0.65	0.04	0.22 < .05	0.09 < .05	0.07 < .01	1	24 < 3	20	498 < 2	< 2	< 5	< 5								
ABK02	4B-01	140.65	578464	6300991	11	95.4	0.2	1	1.4	44.7	6.2 < 1		417.4	2.9	9.5 < 1		2	30 < 1		67.5	2.5	50.3	89.3	8.07	24.2	2.5	0.6	1.55	0.14	0.76	0.09	0.31 < .05	0.19	0.03	1	8	4	38	1325 < 2	< 2	< 5	< 5	
ABK03	4C-01	63.00	578821	6301274	11	67.6	0.2	1.4	1.6	93.2	3.9 < 1		216.9	7.8	27 < .1		5.2	18 < 1		87.8	2.6	50.9	104.6	9.1	29.2	3.2	0.77	1.72	0.15	0.82	0.1	0.33 < .05	0.17	0.02 < 1		6	4	29	924 < 2		0.2 < 5	< 5	
ABK04	5A-02	84.23	582687	6306035	11	90.2	0.1	3.2	4.1	188.6	1.1	1	137.9	17.8	30.9 < .1		3.3	39 < 1		129.1	11.7	194.7	392.9	38.37	130.5	14.7	3.65	6.92	0.73	4.01	0.48	1.33	0.1	0.03	1	22	6	59	1086 < 2		0.4 < 5	0.8	
ABK05	6-02	110.15	585550	6308383	11	87.4	0.2	3.2	3.1	172.3	7.6	1	419.2	12.6	23.2 < .1		3.9	66	1	120.8	10.9	163.6	303.7	29.43	97.2	11.2	3.01	5.55	0.64	3.46	0.44	1.29	0.1	0.66	0.1	1	46	8	60	1103		2 < 2	< 5	< 5	
ABK06	7B-01	76.93	583131	6312089	11	64.3	0.8	5.9	6.3	246	31.1	2	1279.1	17.2	31.7 < .1		7.4	90 < 1		241.6	16.8	233.6	452.6	43.98	148	17.2	4.3	8.5	0.96	5.27	0.64	1.93	0.15	1.03	0.12	1	46	13	73	559		2 < 2	< 5	0.8	
ABK07	7C-01	58.40	583052	6312455	11	68.6	0.4	4.7	6.8	284.2	8.8	2	1581.6	21.4	37.1 < .1		6.2	78 < 1		323.5	19	320.7	596.2	57.65	197.9	21.7	5.6	13.87	1.11	6.25	0.74	2.26	0.17	1.03	0.13	1	51	10	62	376 < 2		0.4 < 5	0.5	
ABK08	11-01	55.50	619724	6320041	11	115.5	0.3	2.8	1.7	89	11.7	1	272.5	7.6	10.2	0.1	2	64 < 1		59.3	3.9	50.8	88.6	8.24	25.8	2.7	0.55	1.66	0.17	0.93	0.14	0.46	0.15	0.36	0.05	1	9	5	48	1200 < 2		0.2 < 5	0.5	
ABK09	11-01	135.50	619724	6320041	11	96.6	0.5	3.7	3.9	116.8	15.5	1	601.3	7.1	14.7	0.2	3.8	57 < 1		141.8	5.4	101	172.9	15.45	48.7	4.7	1.08	2.41	0.25	1.47	0.19	0.64	0.06	0.4	0.06	1	10	10	60	1102 < 2		0.2 < 5	0.5	
ABK10	14-01	14.56	582883	6315050	11	86.9	0.5	3.4	3.7	133	14.1	2	624.3	9.6	19	0.6	4.3	44	2	138.6	10.1	141.3	283.4	27.4	91.5	10.6	2.76	5.08	0.58	3.08	0.31	0.41	1.18	0.12	0.57	0.11	< 1		24	6	50	1280 < 2		0.2 < 5	< 5	
ABK11	14B-03	30.17	582820	6315277	11	100.1	0.2	3.1	3.4	117.1	6	1	336.8	8.2	15.4	0.1	3.3	41 < 1		124.6	8.7	118.4	232.6	22.76	77.2	9.3	2.28	4.51	0.49	2.7	0.34	0.98	0.08	0.52	0.07	1	26	6	53	1340	2 < 2	< 5	< 5	
ABK12	14C-06	54.30	583030	6315357	11	87.3	0.3	2.6	4.1	158.3	6.6	1	737.3	11.3	20.5 < .1		4.7	51 < 1		162.2	10.4	163.7	312.5	30.96	105.8	12.1	3.11	5.58	0.61	3.41	0.39	1.17	0.1	0.58	0.07	1	32	8	53	1279 < 2		0.2 < 5	< 5	
ABK13	14C-06	54.30	583030	6315357	11	91.4	0.3	2.1	4.5	172.5	6.1	2	773.7	12.5	22.9	0.3	4.6	53 < 1		175	11.1	176.4	341.8	33.69	112.6	13	3.33	6.33	0.88	3.66	0.44	1.33	0.1	0.63	0.07 < 1		32	7	54	12				
ABK14	19-03	19.85	575034	6289104	11	46.2	2.3	7.9	3	122	57	2	859.1	6.6	18.4	0.2	6.1	81	2	127.2	13.9	109.8	196.4	18.66	62.6	8.5	2.01	4.67	0.56	3.22	0.5	1.47	0.16	1.11	0.16	1	23	17	58	567	9	0.4	0.7 < 5	
ABK15	91-03	84.93	581820	6317052	11	88.6	0.4	2.7	5.8	208.8	22.6	2	1301.1	12.7	23.9 < .1		4.8	65 < 1		246.3	12.9	210.5	400.2	39.46	134.9	15.4	3.88	7.25	0.76	4.24	0.5	1.46	0.11	0.69	0.07	1	61	9	58	1262 < 2		0.2 < 5	0.6	
ABK16	155-01	102.50	581763	6293954	11	84.5	0.8	4.6	2.3	135.7	22.6	2	566.3	9.4	26.3 < .1		3.1	77 < 1		88.9	7.2	145.1	262.1	23.49	70	7	1.69	3.18	0.36	2.09	0.26	0.88	0.07	0.52	0.07	1	25	10	56	1009 < 2		0.2 < 5	0.7	
ABK17	155-01	148.60	581763	6293954	11	87.2	0.5	3.9	2	121.2	10	1	691.2	8.2	22.4 < .1		3	75 < 1		87.5	6.9	128.2	229.6	20.11	58	6.1	1.5	2.87	0.37	1.98	0.26	0.82	0.08	0.49	0.07	1	22	11	54	1077 < 2		0.2 < 5	0.7	
ABK18	155-01	148.60	581763	6293954	11	101.7	0.2	3.8	1.6	120.2	5.2	1	646.8	8.5	22.3 < .1		3	69 < 1		78.5	6.4	107.9	190.3	17.33	52.2	5.4	1.39	2.74	0.32	1.92	0.25	0.74	0.06	0.47	0.07	1	21	8	54	11				
ABK19	BM2-01	52.00	632349	6309823	11	10.4	5.1	15.1	7.5	11	87.4	2	179.5	1	8	0.2	3.1	156	1	286.1	21.6	28.2	57.1	6.58	25.2	4.7	1.11	4.14	0.62	3.7	0.75	2.49	0.32	2.13	0.33	1	17	11	94	16	13	0.2 < 5	< 5	
ABK20	BM2-01	79.50	632349	6309823	11	62.5	1.9	5.7	3	183	122.6	2	1464.5	12.3	20.7 < .1		5.8	139	3	135.6	15.3	150.2	274.7	26.96	95.5	11.7	2.88	6.3	0.72	4.01	0.54	1.64	0.14	0.98	0.14	4	48	13	57	766	2	0.6 < 5	0.9	
ABK21	BM2-01	103.30	632349	6309823	11	83.7	0.8	4.8	4	245.4	19.5	2	389.3	17.1	26.4 < .1		7.6	130	1	168.9	15.5	196.6	359	35.6	122.8	14.5	3.71	7.15	0.82	4.52	0.58	1.67	0.14	0.91	0.12	1	63	12	62	936	2	0.2 < 5	1.1	
ABK22	BM2-01	113.80	632349	6309823	11	76.6	0.7	6.2	3.6	253.3	16.7	2	664.7	15.5	23.5 < .1		7.6	138	3	157.9	15.2	199.6	357.6	34.64	118.7	14.9	3.62	7.19	0.78	4.47	0.56	1.66	0.14	0.89	0.11	1	62	11	57	841	2	0.4 < 5	0.5	
ABK23	BM3-01	124.90	631219	6314208	11	55.6	2.3	8	3	123.3	56.9	2	847.5	6.5	17.7 < .1		5.5	96	2	123	14.3	113.9	197.2	19.4	65.6	8.5	2.18	4.59	0.55	3.35	0.51	1.57	0.18	1.08	0.16	< 1		22	14	53	999	8	0.5 < 5	0.7	
ABK24	BM3-01	144.90	631219	6314208	11	34.9	4.9	12.4	4.6	125.5	135.9	2	933.1	7.9	19.6 < .1		5.4	173	2	171.8	19	134.2	247.7	24.55	86.5	11.4	2.8	6.17	0.8	4.72	0.77	2.2	0.23	1.59	0.24	2	47	15	82	203	2	0.9	0.8	0.8
ABK25	LL8-01	77.80	629936	6301692	11	61.5	0.4	0.8	1	38	9.1 < 1		393.7	2.6	9.1 < .1		1.6	24 < 1		40.2	1.7	25.1	44.4	3.93	12	1.3	0.32	1.08	0.08	0.41	0.05	0.2 < .05	0.15	0.02	1	3 < 3		23	929 < 2		< 2	< 5	< 5	
ABK26	LL8-01	121.50	629936	6301692	11	102.5	0.4	1.8	0.8	48.3	5.8	1	123.5	2.3	8.3 < .1		1.8	42 < 1		35.8	3.5	37.8	65.4	5.71	17.3	1.9	0.5	1.48	0.13	0.72	0.14	0.42 < .05	0.31	0.05	1	5	3	46	1519 < 2		< 2	< 5	0.9	
ABK27	LL8-01	144.90	629936	6301692	11	111.9	0.6	1.6	0.9	72.6	17.9	1	259.1	4.5	15 < .1		3.2	35 < 1		40.5	2.3	46.6	86.9	7.47	22.8	2.2	0.57	1.52	0.1	0.71	0.09	0.26 < .05	0.18	0.03	1	3	3	38	1445 < 2		< 2	< 5	0.6	
ABK28	K5 (surface)	surface O/C	582432	6306145	11	80.8	1.5	4.2	2.8	108.3	10.3	1	450.8	8.5	15.1 < .1		2.9	64 < 1		107	9.1	109.9	212.2	20.74	69.1	8.3	2.12	4	0.46	2.66	0.35	1.11	0.1	0.65	0.09	1	19	6	46	1123 < 2		< 2	< 5	0.5	
ABK29	K6 (surface)	surface O/C	585317	6308651	11	79.6	0.5	3.9	3.2	130.1	26.5 < 1		789.3	9.8	18.1	0.1	3.1	125 < 1		111.9	9.2	133.7	247.5	23.91	82.1	9.6	2.48	4.77	0.53	2.69	0.39	1.06	0.1	0.56	0.09	1	38	5	48	1058 < 2		0.2 < 5	< 5	
ABK30	K14 (surface)	surface O/C	582894	6315185	11	80.7	0.3	2.9	3.9	147.2	14.6 < 1		1162.3	10.7	20.6	0.1	4.3	73	1	157.4	10.6	159.9	313.7	30.29	102.6	11.5	2.98	5.77	0.63	3.33	0.43	1.31	0.11	0.64	0.09	1	30	6	51	1206 < 2		< 2	< 5	0.5	
ABK31	ML95-1	7.22	454636	6145914	11	32.1	3.2	13.3	3.8	83.6	76	1	443.2	5.7	15.6	0.2	3.4	138	2	146.6	16.8	74.9	136.1	14.24	50.4	7	1.85	4.33	0.59	3.44	0.64	1.88	0.24	1.66	0.26	2	49	11	75	435	4	0.7 < 5	< 5	
ABK32	ML95-1	35.00	454636	6145914	11	25.7	4	15.5	3.8	46.2	104.2	1	322.5	2.9	11.2	0.2	3.5	115	2	129.5	18.1	50.6	93.3	9.66	35.4	5.4	1.48	4.09	0.56	3.34	0.65	2.02	0.27	1.71	0.25	1	37	11	74	219	7	0.6 < 5	< 5	
ABK33	ML95-1	35.00	454636	6145914	11	26.7	4.3	16	3.7	46.9	104.8	1	319	3	11	0.3	3.5	109	3	128.8	18.1	50.2	92.9	9.41	35.6	5.5	1.4	4.12	0.55	3.32	0.67	2.01	0.26	1.74	0.27	1	38	11	75	2				
ABK34	ML95-1	64.00	454636	6145914	11	21.2	2.7	7.8	2.5	41.8	41.5 < 1		327.1	2.6	8.3	0.3	2.3	68	2	88.7	21.7	57.9	100.2	10.08	39	6	1.51	4.76	0.63	3.58	0.72	2.14	0.25	1.67	0.22	6	29	7	43	156	7 < 2	< 5	< 5	
ABK35	ML95-1	95.00	454636	6145914	11	33.5	3.6	14	3.7	75	80.9	1	441.7	4.5	13.2	0.5	3.8	126	2	146.5	18.3	69.7	130	12.87	47.8	6.7	1.86	4.6	0.6	3.51	0.68	2.09	0.25	1.67	0.26	2	46	11	75	306	4	0.7 < 5	< 5	
ABK36	ML95-1	134.10	454636	6145914	11	26.2	3.6	13.3	3.7	45.4	82.9	1	365.7	2.9	10.6	0.2	3.4	106	2	142.2	16.4	49	90.2	9.26	35.2	5.3	1.18	3.89	0.5	3.09	0.59	1.85	0.23	1.6	0.26	1	36	9	72	223	5	0.6 < 5	< 5	
ABK37	ML95-1	134.10	454636	6145914	11	25.8	3.4	13.9	3.6	41.1	82.4	1	353	2.5	9.4	0.5	3.1	102	2	133.4	15.8	44.1	81.7	8.44	31.6	4.8	1.14	3.68	0.48	2.96	0.58	1.76	0.24	1.5	0.23	1	36	10	71	2				
ABK38	ML95-1	161.90	454636	6145914	11	48.1	3.5	13.1	3.7	87.5	69.9	1	544.3	5.5	15	0.7	3.7	124	4	142	17.4	80.7	147.1	14.58	52.9	7	1.84	4.62	0.61	3.6	0.63	1.98	0.22	1.59	0.23	2	48	10	74	525	6	0.6 < 5	< 5	
ABK39	ML95-3	7.45	454779	6145324	11	46.5	2.8	11.2	3	80.2	72.7	1	487.9	5	12.6	0.2	3.4	115	2	115.1	14.8	70	125.4	12.54	44.9	6	1.62	3.97	0.49	2.83	0.53	1.58	0.19	1.36	0.19	1	45	9	64	550	4	0.6 < 5	< 5	
ABK40	ML95-3	29.80	454779	6145324	11	40.4	4	11.1	3.1	70.6	72.9	1	423.4	4.5	12.1	0.5	3.2	110	2	113	15.2	63.4	115	11.43	41	5.8	1.61	4.09	0.51	3.11	0.54	1.68	0.2	1.35	0.2	2	45	9	70	495	5	0.9 < 5	< 5	
ABK41	ML95-3	60.00	454779	6145324	11	54.9	1.9	13.5	3.2	77.2	55.9	2	428.9	4.9	12.9	0.6	3.1	103	4	121	13.7	66	117.8	11.75	42.2	6	1.53	3.71	0.51	2.68	0.52	1.44	0.22	1.25	0.2	3	42	9	65	732	5	0.4 < 5	< 5	
ABK42	ML95-3	60.00	454779	6145324	11	55.8	1.9	12.7	2.9	83.2	64.6	1	456.7	5.2	13.3	0.6	3	106	3	118.3	13.9	70.1	127.1	12.71	45.6	6	1.55	4.03	0.51	3.02	0.52	1.59	0.19	1.27	0.17	4	43	9	66	7				
ABK43	ML95-3	88.80	454779	6145324	11	54	1.9	9.8	2.7	87.2	57.5	1	465.9	5.4	13.4	0.6	3.1	102	2	112.8	13.5	74.4	136.5	13.17	46.2	5.9	1.64	3.65	0.49	2.84	0.46	1.46	0.17	1.21	0.19	2	45	9	65	670	4	0.5 < 5	< 5	
ABK44	ML95-3	117.90	454779	6145324	11	50.1	2.6	10.5	2.9	80.3	75.5	1	466.3	5.1	12.9	0.3	3.3	110	2	114.9	14.8	70.1	127.6	12.76	45.3	6	1.64	4.01	0.53	3.06	0.52	1.58	0.19	1.24	0.2	2	45	9	68	603	7	0.5 < 5	0.5	
ABK45	ML95-3	133.90	454779	6145324	11	49.5	2.7	11.8	3.4	81.5	65.7	1	470.4	5	13.2	0.3	3	115	3	136.7	15	70.8	130	12.65	43.9	6.1	1.52	4	0.51	3.05	0.53	1.66	0.19	1.33	0.2	3	47	10	68	585	4	0.5 < 5	< 5	
ABK46	ML95-3	165.00	454779	6145324	11	44.1	3.7	12.1	3.6	79.2	79.2	1	432.4	4.8	13	0.2	3.6	117	2	133.1	15.4	68.9	128.1	12.74	45.5	6.2	1.6	4.04	0.56	3.17	0.54	1.8	0.22	1.43	0.2	1	46	11	73	510	6	0.7 < 5	< 5	
ABK47	ML95-3	165.00	454779	6145324	11	43.5	3.8	12.2	3.4	78.7	84.9 < 1		419.6	5	13	0.2	3.6	123	2	132.7	15.9	69.5	126.8	12.78	45.1	6.7	1.66	4.23	0.53	3.14	0.57	1.76	0.21	1.45	0.21 < 1		48	10	71	4				
ABK48	98DH-XE01	87.70	376850	6347300	12	50.3	0.5	7.2	4.3	135.4	69.8	1	841.8	5.7	17.1	0.4	5.2	158	5	160.6	14.3	81	159.9	16.06	58.2	8.1	3.94	5.03	0.67	3.52	0.56	1.58	0.17	1.06	0.15	15	61	15	62	451	3	0.8	0.5	0.5
ABK49	98DH-XE01	153.96	376850	6347300	12	40.2	4.2	14.1	5	104.8	92.5	2	687.3	6.4	16.2	0.5	4.7	156	2	160.9	20.4	84.6	171.8	17.58	64.3	9.2	2.3	5.63	0.75	4.11	0.75	2.15	0.25	1.69	0.23	1	52	13	77	350	6	0.6 < 5	0.5	
ABK50	98DH-XE01	153.96	376850	6347300	12	37.5	4.1	12.4	4.9	97	85	1	592.3	6	15.1	0.4	4.2	148	2	163.1	18.6	77.3	156.1	16.05	59.3	8.8	2.19	5.37	0.86	3.9	0.71	2.24	0.25	1.65	0.25	1	48	13	78	3				
ABK51	98DH-RI001	123.00	365051	6357585	12	50.8	2.9	10.4	5.6	187.7	95.1	2	880.6	9	25.4	0.3	4.9	149	1	234	21.9	189.8	340.6	32.81	113.2	13.9	3.66	7.21	0.89	5.23	0.82	2.42	0.24	1.57	0.22	2	52	18	73	239	7	0.6 < 5	< 5	
ABK52	98DH-PH02	137.00	351550	6330493	12	73.8	0.3	5.9	4.7	280.6	18.6	2	1081.7	11.4	46.6	0.1	6.8	106 < 1		189.5	14.7	287.2	509.2	47.37	156.5	16.3	4.22	7.75	0.85	4.74	0.58	1.65	0.13	0.81	0.08	4	73	14	58	468 < 2		< 2 < 5	< 5	
ADK53	98DH-PE01	100.00	374692	6368251	12	84.7	0.8	5.8	3.6	215.6	35.6	1	780	15.6	39	0.1	5	90	3	135.1	15.1	200.2	386.5	37	127.8	14.4	3.7	6.66	0.74	4.34	0.55	1.72	0.16	0.94	0.12	2	45	12	62	787 < 2		0.2	0.6 < 5	
ABK54	98DH-PE01	100.00	374692	6368251	12	91.8	0.9	6.5	3.9	219.8	33.3	2	776.8	16.8	39.6	0.2	5	90	3	137.4	15.2	207.8	391.5	37.76	131.2	14.6	3.76	7.09	0.83	4.35	0.58	1.74	0.15	0.99	0.13	2	45	11	65	8				
ABK55	98DH-PE01	128.00	374692	6368251	12	10.9	7.5	15.7	3.1	13	109.7	2	174.5	1.1	8.4	0.4	2.7	180	2	112.2	19.6	43	84	9.12	34.9	5.1	1.26	4.06	0.53	3.37	0.69	2.2	0.28	1.95	0.29	1	26	13	92	24	14	0.4 < 5	0.7	
ABK56	98DH-PE01	170.00	374692	6368251	12	74.3	0.7	6.6	4.5	248	47.1	1	883.3	14.8	30.3	0.1	5	129 < 1		169	15.3	212	386.7	37.44	129.9	15.1	3.79	7.16	0.78	4.34	0.56	1.69	0.15	0.9	0.12 < 1		69	13	63	632 < 2		< 2 < 5	< 5	
ABK57	98DH-LE01	12.20	386200	6340600	12	77.1	1	7.1	5.2	229.9	32.1	2	780.2	17.7	31.9	0.1	5.7	134	1	189.8	12.1	164.6	295.7	27.35	90.8	10.1	2.52	4.9	0.56	3.3	0.45	1.35	0.12	0.81	0.11	2	56	10	59	608 < 2		0.2 < 5	< 5	
ABK58	98DH-LE01	22.00	386200	6340600	12	88.4	1.1	7.2	5.1	238.2	37.9	4	704.9	21	37.2	0.5	6.2	153	1	183.3	12.3	173.7	295.9	27.05	85.9	10.3	2.52	4.88	0.64	3.66	0.5	1.31	0.11	0.8	0.12	1	65	11	90	658	2 < 2		0.7 < 5		
ABK59	98DH-LE01	44.00	386200	6340600	12	89.4	1	7.4	5.5	253.8	34.8	2	736.6	23.4	37.7 < .1		6	145	2	202.2	13.1	187.3	322.8	30.06	98.2	11.7	2.83	4.88	0.63	3.98	0.53	1.33	0.12	0.88	0.12	2	65	11	73	636	2 < 2		< 5	< 5	
ABK60	98DH-LE01	44.00	386200	6340600	12	90.4	1	8	6.5	268.5	37.5	3	809.7	22.1	37.3	0.5	6	136	1	201.9	14	202.8	344.5	32.05	101.5	12	2.95	5.22	0.85	4.08	0.57	1.46	0.13	0.81	0.11	2	67	11	80	6				
ABK61	98DH-LE01	58.00	386200	6340600	12	89.8	1.3	7.6	5.9	256.3	36.4	3	792.9	22.6	39.6	0.7	6.3	171	1	207.4	13.9	187.4	324	30.33	95.7	11	2.88	5.16	0.71	4.15	0.56	1.49	0.15	0.91	0.12	3	62	11	71	607	2 < 2	< 5	< 5	
ABK62	98DH-LE01	81.90	386200	6340600	12	87	1	7.7	5.5	257.5	31.2	4	819.6	22.6	38.1	0.8	6.9	150	2	204.1	13.9	181	307.6	28.48	89.9	10.7	2.7	5.29	0.7	4	0.6	1.46	0.17	0.95	0.17	5	61	11	61	607	2 < 2	< 5

Appendix 4a - Scatter-Plot Matrix of Selected Major and Trace Elements for the Mountain Lake Diatreme Samples Versus the Sweet Grass Minettes.

Appendix 4b - Scatter-Plot Matrix of Selected Major and Trace Elements for the Buffalo Head Hills Samples Versus Worldwide Kimberlite.

Appendix 4c - Scatter-Plot Matrix of Selected Major and Trace Elements for the Birch Mountains Samples Versus Worldwide Kimberlite.